Toward Quantum-Limited Axion Detection: A Mitigation Strategy

July 1, 2025

Yannis K. Semertzidis, KAIST

Axions in Stockholm, Nordita, Stockholm, Sweden

June 23 to Jully 11, 2025

- "Cosmic Axions Revealed via Amplified Modulation of Ellipticity of Laser (CARAMEL),"
- Based on EO detection of the axion induced electric field in microwave cavity plus probing
- A new approach to reading out axion haloscopes could increase the axion frequency scanning rate by more than an order of magnitude, enabling its detection or exclusion in less than five years (axions after inflation).

arXiv:2506.24022v1 [hep-ex] 30 Jun 2025

Cosmic Axions Revealed via Amplified Modulation of Ellipticity of Laser (CARAMEL)

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Major recent breakthroughs in axion dark matter research

- Josephson parametric amplifiers with noise near quantum limit
- High field, large volume magnets
- Large volume cavities cooled to <30mK
- New resonating geometries/concepts: high frequency resonances made available for large volume microwave cavities
- High quality factors at high magnetic fields using HTS tapes
- CAPP contributed to all of the above successes (yes, the field is ready for large scale effort).
- Nonetheless, we still need a few decades to completely cover all interesting frequencies at DFSZ sensitivities.

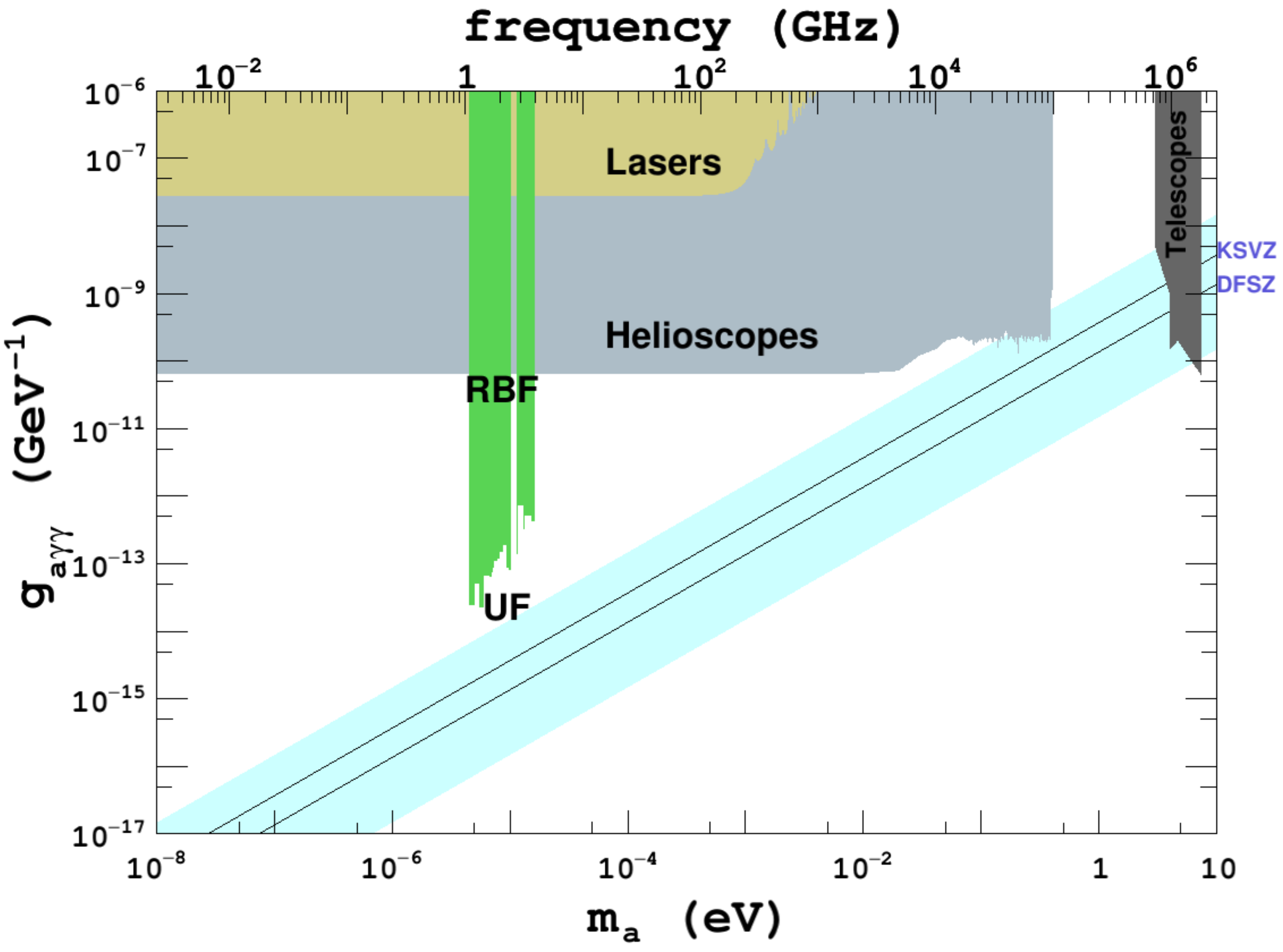
- With CARAMEL, we aim to help reach better than DFSZ sensitivity with less than 3s integration time per step. Covering interesting range in <5 years.

Rochester Brookhaven Fermilab axion dark matter search

- The RBF-dark matter axion group, circa 1990
- Under the leadership of Adrian C. Melissinos (Rochester), 1929-2022, a daring pioneer, full of energy, a great teacher.

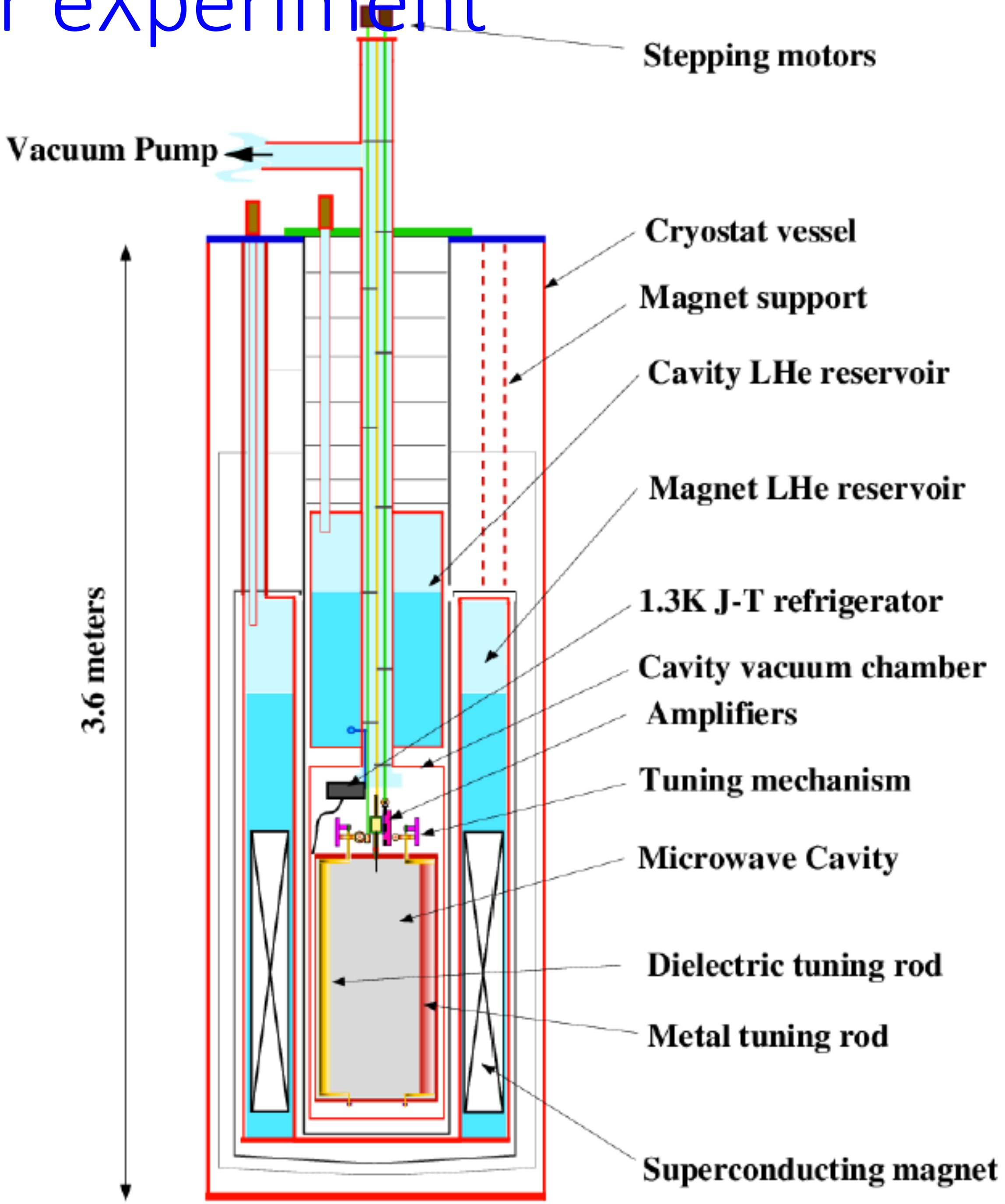
First haloscope limits:
Rochester,
Brookhaven,
Fermilab.

Then
University of
Florida



Axion Dark Matter eXperiment

- Cryogenics (0.1K)
- Superconducting magnet (>7.5 T)
- Large volume cavity (140*l*)
- Low noise amplifiers
  - From 12K to 1K
  - Currently SQUID and JPA (<1K)



Axion dark matter reviews

Axion dark matter review articles, theory and experiments

- Axion dark matter: What is it and why now?

By Francesca Chadha-Day, John Ellis, David J.E. Marsh, *Sci. Adv.* **8**, eabj3618 (2022)

- Axion dark matter: How to see it?

By YkS and SungWoo Youn, *Sci. Adv.* **8**, eabm9928 (2022)

- What can solve the Strong CP problem?

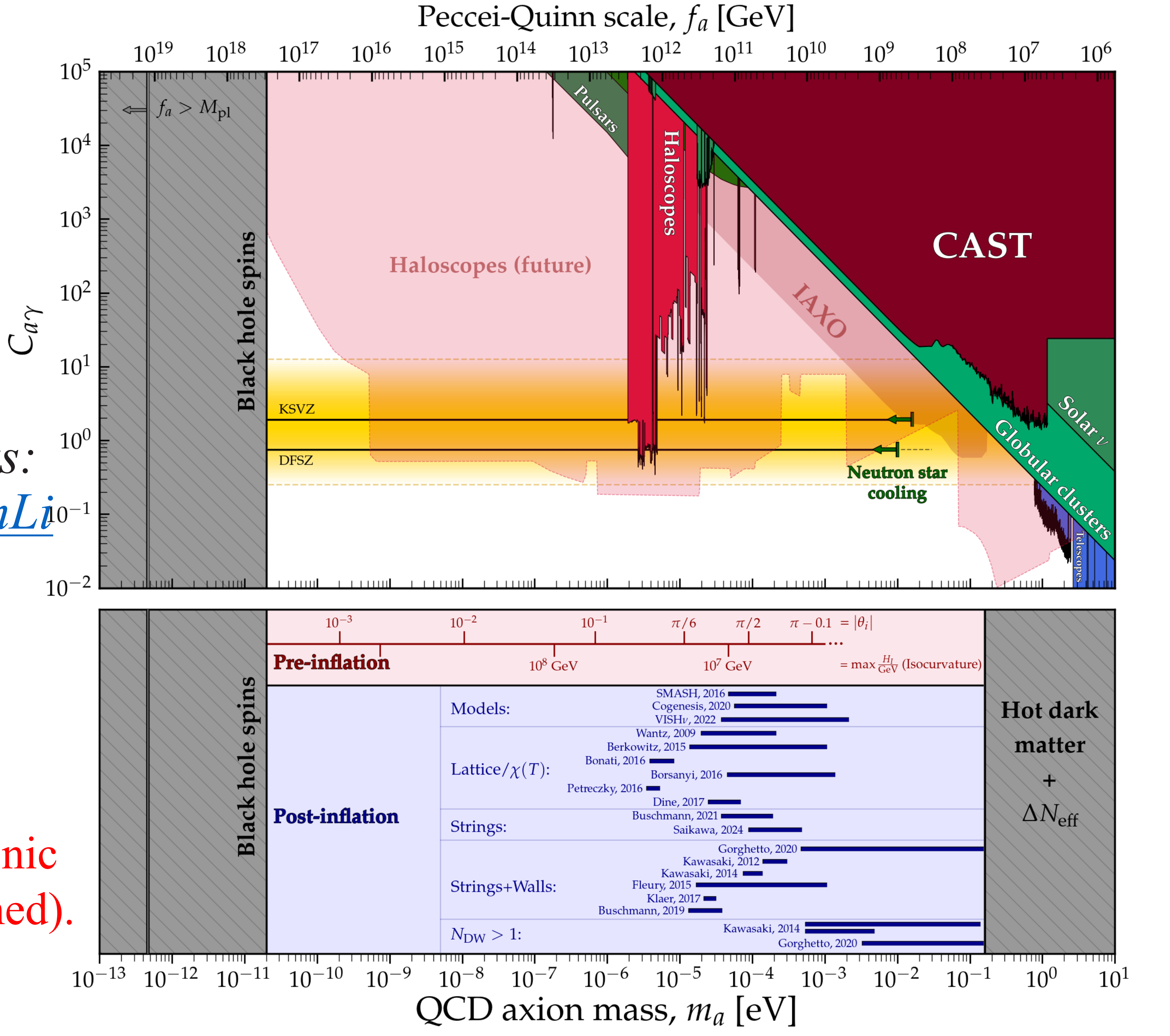
By David E. Kaplan, Tom Melia, Surjeet Rajendran, arXiv: 2505.08358

What is known about DM?

- Cosmic density [strong evidence: CMB anisotropies (*13*)]. Expressed as a fraction of the total density of the universe, DM makes up 26% of the universe, compared to 6% in ordinary matter and 68% in vacuum energy.
- Local density (strong evidence: Milky Way stellar motions). The local density of DM is around 0.3 to 0.4 GeV cm^{-3}, equivalent to one proton every few cubic centimeters or one solar mass per cubic lightyear. The density is measured, on average, over a relatively large fraction of the galaxy. The actual density at the precise location of Earth could be substantially different. This is particularly relevant to axions, as discussed below. The local density is around 10^5 times the average cosmic density.
- Local velocity dispersion (strong evidence: Milky Way stellar motions). The velocity dispersion of DM is around $\sigma_v = 200\,\text{km s}^{-1}$, and our local motion with respect to the galactic rest frame is in the direction of the constellation Cygnus.
- No preferred galactic length scale (strong evidence: galaxy clustering and evolution). DM must be nonrelativistic ($v \sim c$ would allow DM to move significant distances during galaxy formation) and have negligible pressure (which would imprint sound waves during galaxy formation). This discounts standard model neutrinos and other "hot" or "warm" DM. For bosons, the de Broglie wavelength (which can be modeled as an effective pressure) must be small compared to the galaxy clustering scale.
- Early appearance of DM (strong evidence: galaxy clustering). DM had to be present, as well as gravitating, in the universe long before the CMB formed, and its gravitational influence began before the universe was 1 year old. For light bosonic DM (such as the axion), this corresponds to the latest epoch of particle creation (t_{cold} in Fig.4).
- Lack of significant interactions [strong evidence: the "Bullet Cluster" (*17*)]. DM cannot interact with itself or ordinary matter too strongly.

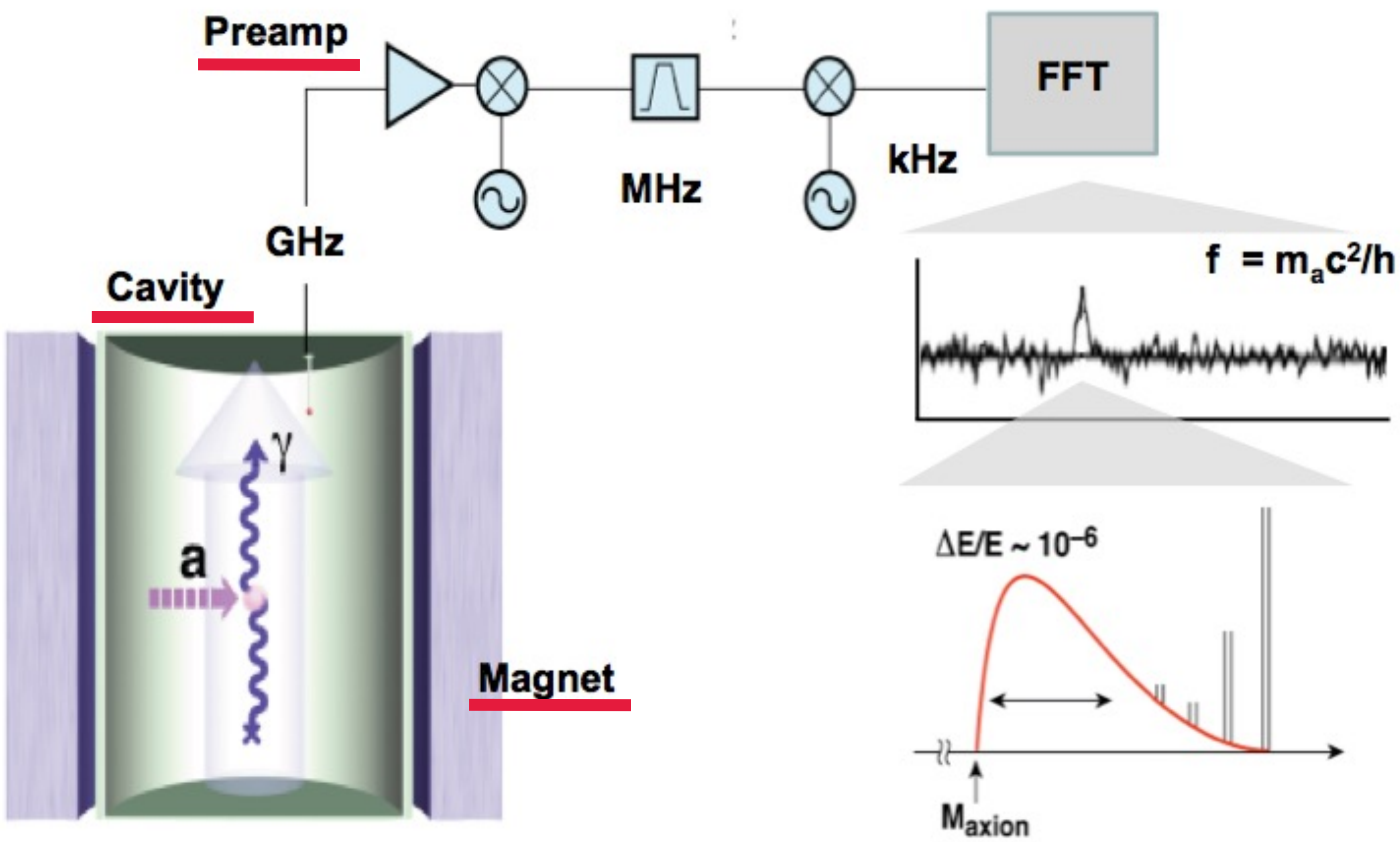
Axion mass predictions

C. O'Hare, cajohare/axionlimits: [*https://cajohare.github.io/AxionLimits/*](https://cajohare.github.io/AxionLimits/)



Lattice QCD recently became more powerful, see, e.g., muon g-2 hadronic correction (still needs to be confirmed).

Haloscope method method suggested by Pierre Sikivie (1983)



$$P_{sig} \propto (B^2 V Q_{cav})(g^2 m_a \rho_a) \sim 10^{-23}\,W \qquad s/n = \frac{P_{sig}}{kT_{sys}}\sqrt{\frac{t}{\Delta\nu}}$$

State of the art axion haloscopes

The ability to scan fast depends on B-field, Volume, Temperature, and Q_0

$$P_{\rm signal} = 22.51\,\mathrm{yW}\left(\frac{g_\gamma}{0.36}\right)^2\left(\frac{B_{\rm avg}}{10.31\,\mathrm{T}}\right)^2\left(\frac{V}{36.85\,\mathrm{L}}\right)\left(\frac{C}{0.6}\right)\left(\frac{Q_L}{35000}\right)\left(\frac{\nu}{1.1\,\mathrm{GHz}}\right)\left(\frac{\rho_a}{0.45\,\mathrm{GeV/cc}}\right)$$

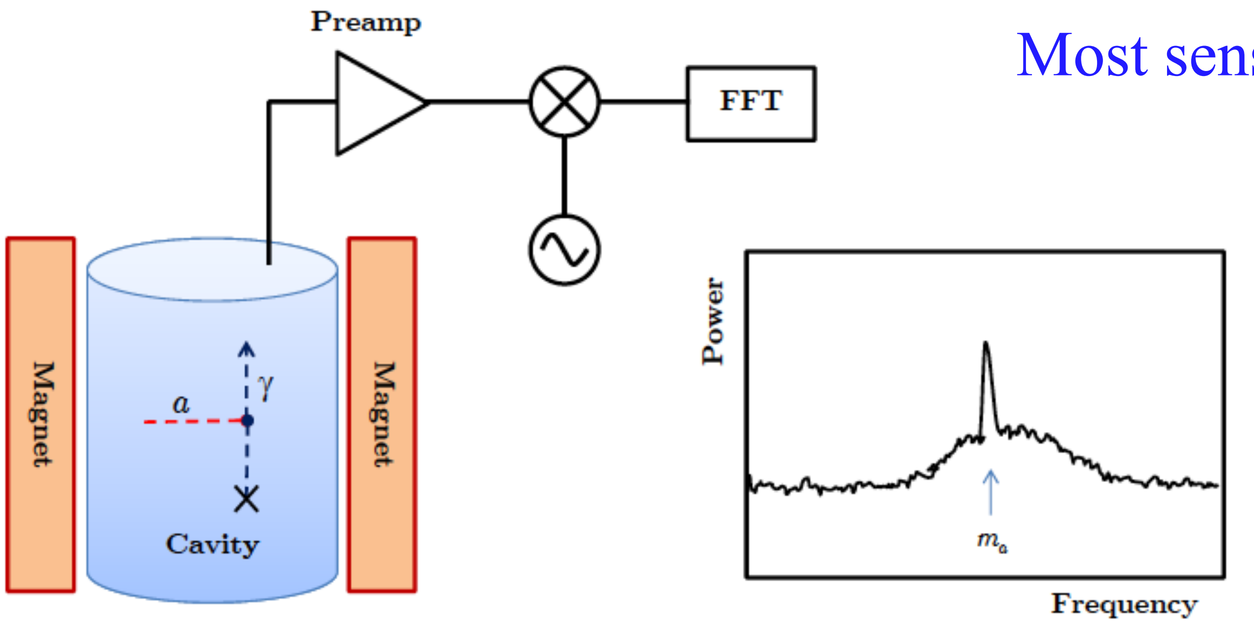


Figure 14: Conceptual arrangement of an axion haloscope. If m_a is within $1/Q$ of the resonant frequency of the cavity, the axion will show as a narrow peak in the power spectrum extracted from the cavity.

Most sensitive method

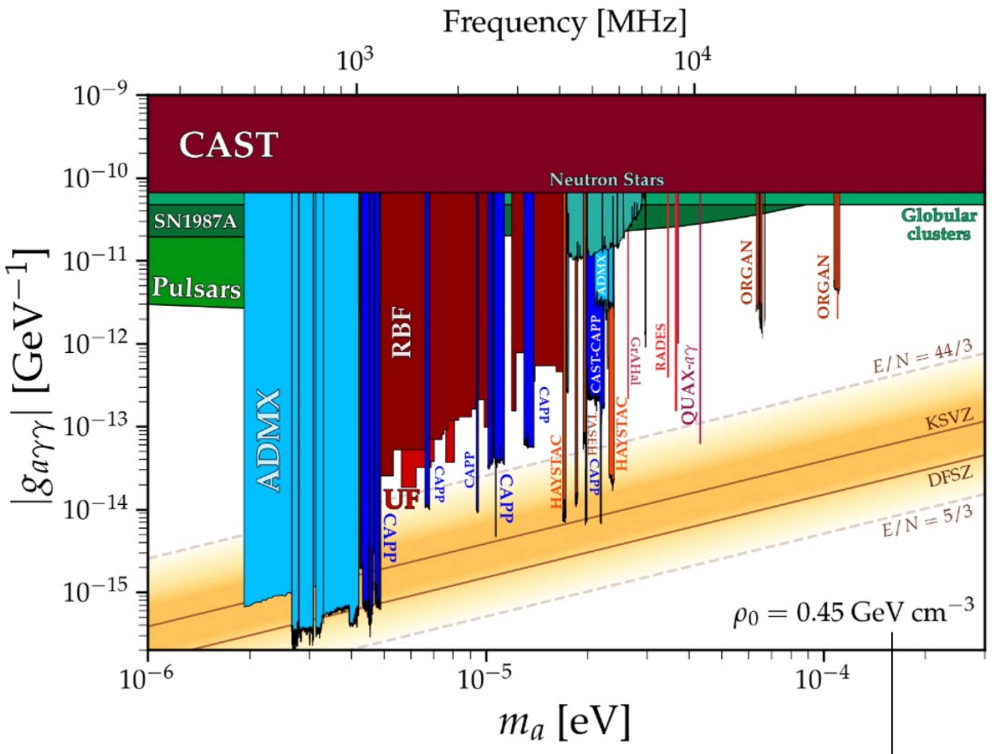
Running Haloscope Experiments:
CAPP→DMAG
ADMX
HAYSTAC

Limits in medium axion frequencies (up to 2024)

Axion haloscope

Slide by Jiwon Lee,
KAIST, PhD work (ongoing)

- The most sensitive method for searching axion dark matter



https://cajohare.github.io/AxionLimits/docs/ap.html

We have assumed axion makes up 100% of the local dark matter density.

← Exclusion limit of Axion haloscope

- Many experiments (CAPP, ADMX, …) have been conducted worldwide.

- **Two axion models**

- Kim-Shifman-Vainshtein-Zakharov (**KSVZ**) $g_\gamma = -0.97$
- Dine-Fischler-Srednicki-Zhitnitskii (**DFSZ**) $g_\gamma = 0.36$

$$g_{a\gamma\gamma} = \frac{\alpha g_\gamma}{\pi f_a}$$

Major activities

- ADMX (UW, microwave cavity)
- HAYSTAC (Yale, microwave cavity)
- IBS/CAPP→DMAG (CULTASK, multiple microwave cavities, 1-10GHz)
- ORGAN (UWA, high frequency)
- QUAX (INFN, microwave cavity)
- KLASH (Large volume magnet in Frascati, microwave cavity)
- MADMAX (DESY, dielectric interfaces)
- ALPHA (Sweden, plasmonic resonance)
- BabyIAXO (DESY, axion helioscope)
- ALPs (DESY, coupled FP resonators)
- CAST-CAPP (CERN, rectangular cavities-TE modes)
- GrAHol-CAPP/DMAG (large volume magnet)
- Dark Matter RADIO and many more, new exciting experiments…!

World map of current experiments on wavy dark matter

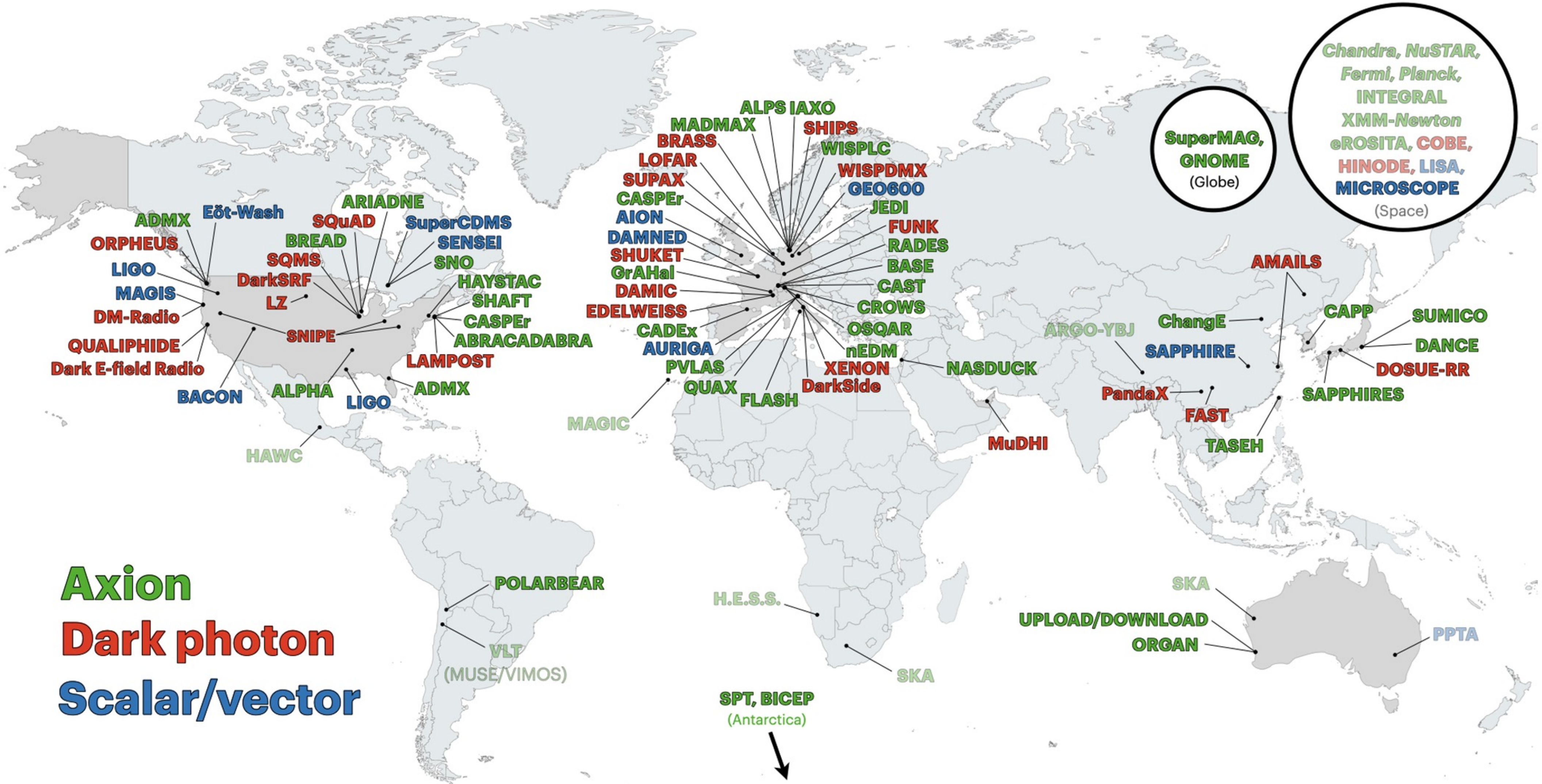


Figure 6: World map displaying current experiments searching for wavy dark matter [9].

There are two major issues with axion research and possibly one solution

- Breakthrough advances are not being openly shared within the community.
- Achieving quantum level sensitivity continues to elude every experiment.

- In order to cover from f_{min}=0.5 GHz to f_{max}=50 GHz and assuming a frequency step of half the axion width (Q_a=10^6) we would need to cover $N = 2Q_a \int_{f_{min}}^{f_{max}} \frac{df}{f} = 2Q_a \ln \frac{f_{max}}{f_{min}} \approx 10^7$ separate steps! (Looking for a radio station in 10million channels.)
- Most current experiments spend/need more than 100s integration time per step for DFSZ sensitivity. That's 30 years at 100% running time efficiency.

- With CARAMEL, we aim to reach better than DFSZ sensitivity with less than 3s integration time per step. A parallel effort could achieve 0.5 – 50 GHz in <5y.

Axion dark matter search

- The axion mass is unknown, like any number in a phone book in New York. The way we look for it:

- Once it's discovered, anyone will be able to dial in… and listen to it.

Axion dark matter search

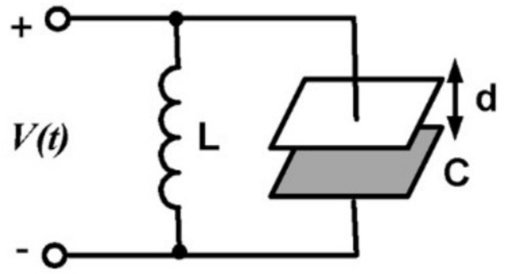
- Once it’s discovered, anyone will be able to dial in… and listen to it.

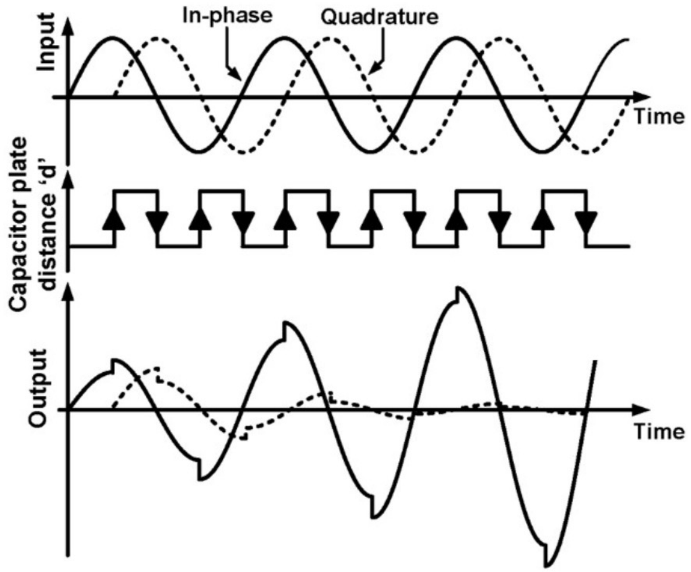
Axion dark matter search

- We need to speed up the dial by developing new, simpler technologies/know-how.

The currently best readout system: Josephson parametric amplifiers (JPA)

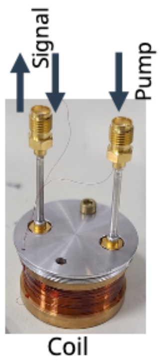
JPA Principle
(Caglar Kutlu's slide, Sergey Uchaikin et al.)



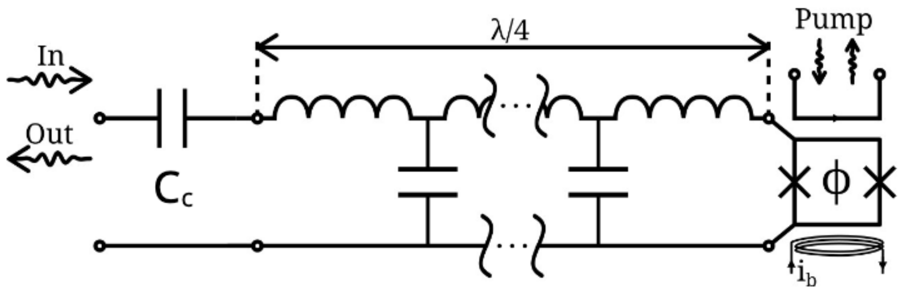


JPA Principle

(no resistors)



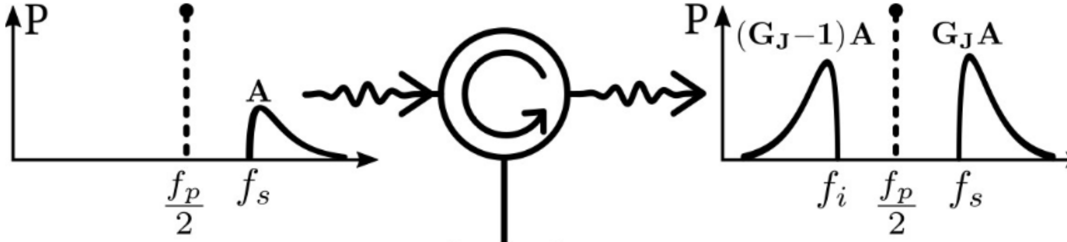
Flux-driven Josephson Parametric Amplifier



$$L_s = \frac{\Phi_0}{2\pi I_c} \frac{1}{\left|\cos\left(\pi \frac{\Phi}{\Phi_0}\right)\right|}$$

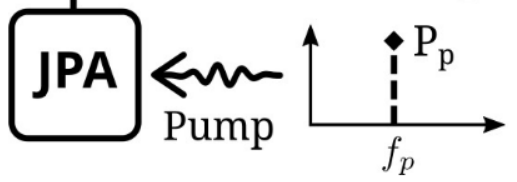
- The "parameter" is the effective inductance of the SQUID.
- With $\phi = \phi_{DC}(i_b) + \phi_{AC}(P_p, f_p)$, the ϕ_{DC} controls bare resonance frequency f_r.
- When the pump tone is present, its amplitude P_p, and frequency f_p determine the dynamics of the system for a certain f_r.

Caglar is now with a quantum computing startup in Switzerland



3 wave mixing operation

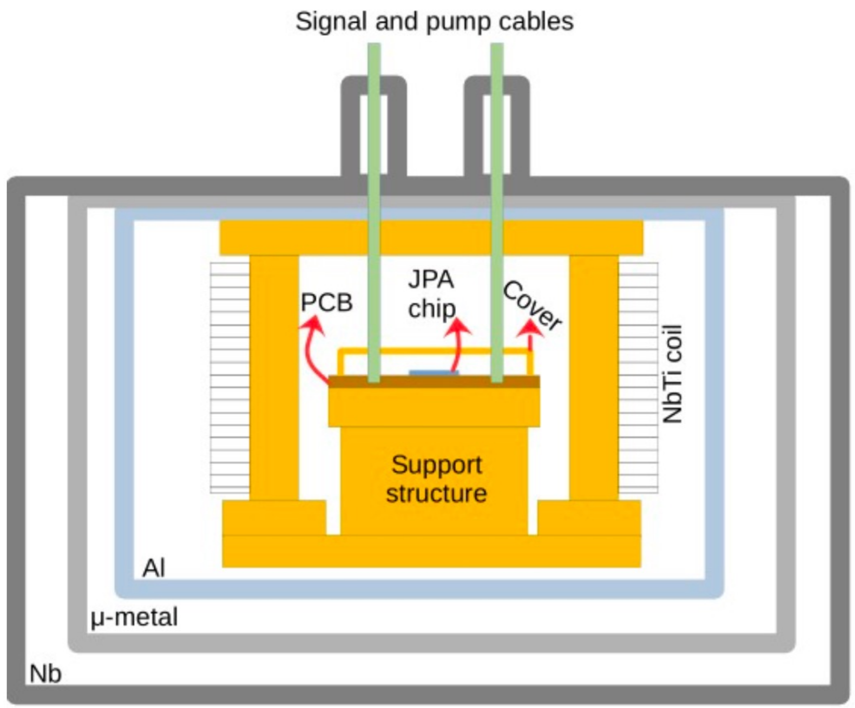
$$f_p = f_s + f_i$$

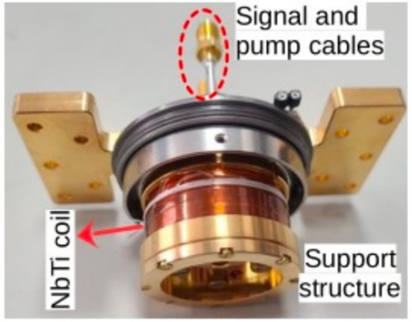


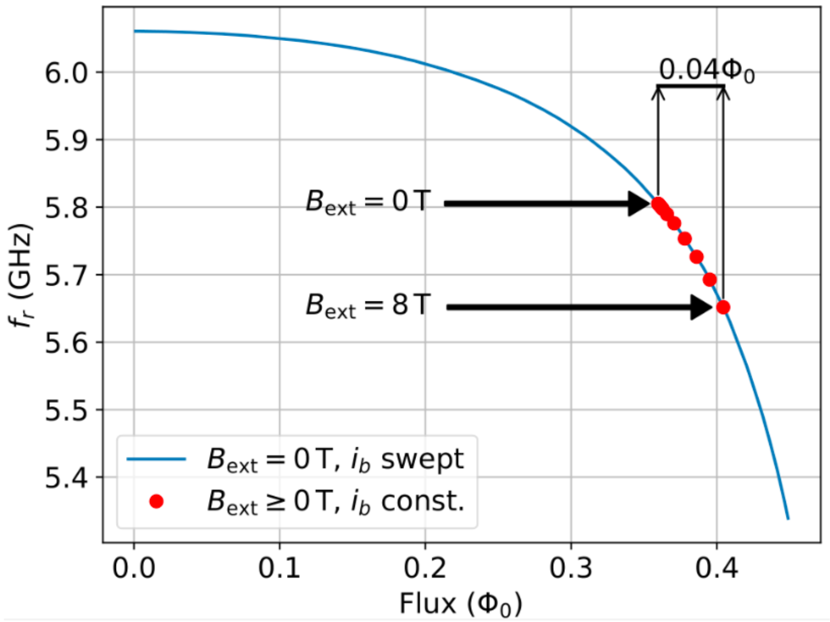
[1] W. Lee and E. Afshari, "A CMOS Noise-Squeezing Amplifier," in IEEE Transactions on Microwave Theory and Techniques, vol. 60, no. 2, pp. 329-339, Feb. 2012

CAPP
Center for Axion and Precision Physics Research

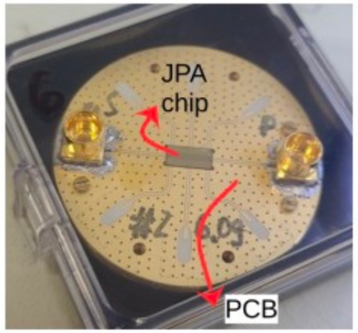
JPA implementation

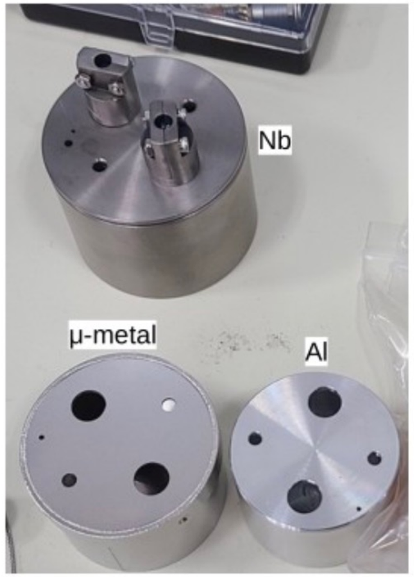




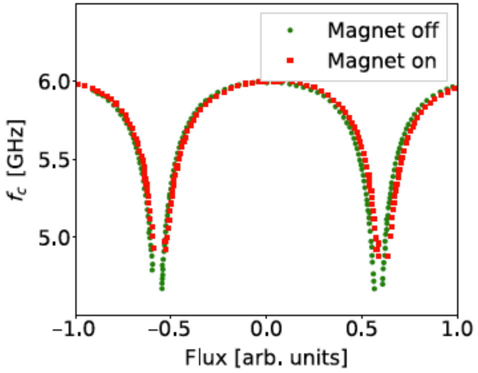


JPA packaging design: Sergey Uchaikin





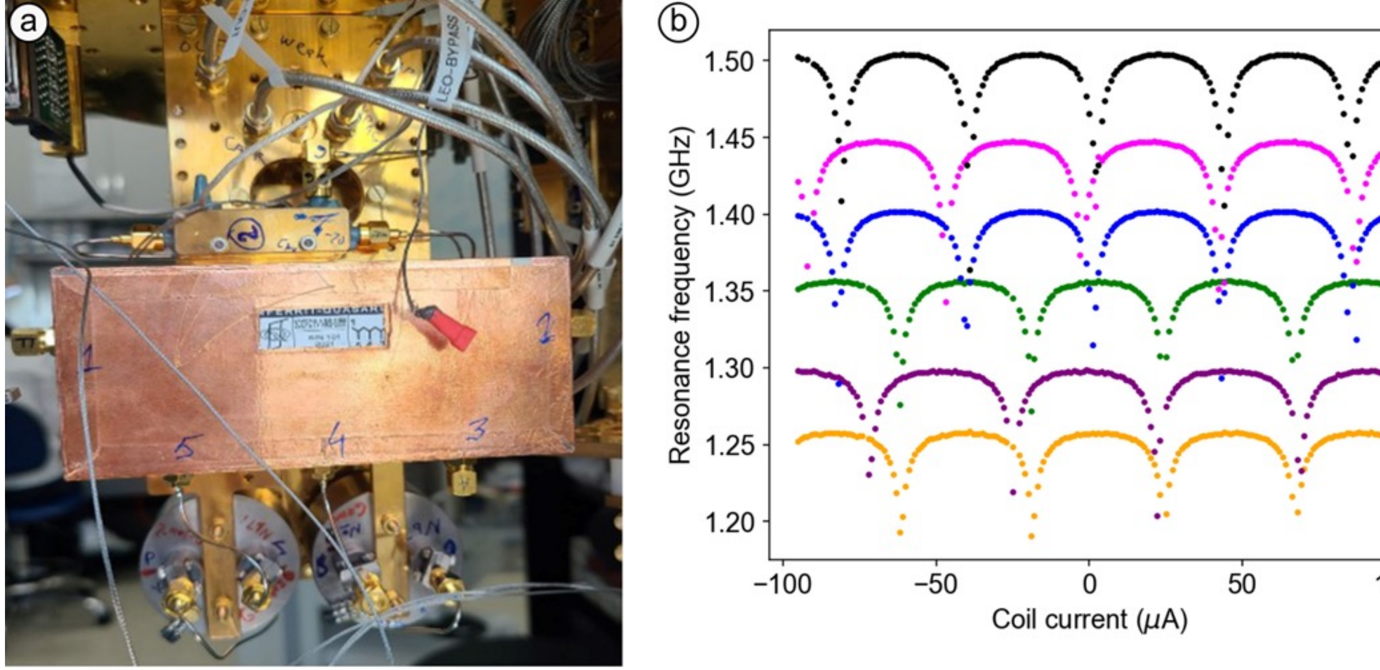
Caglar Kutlu's slide

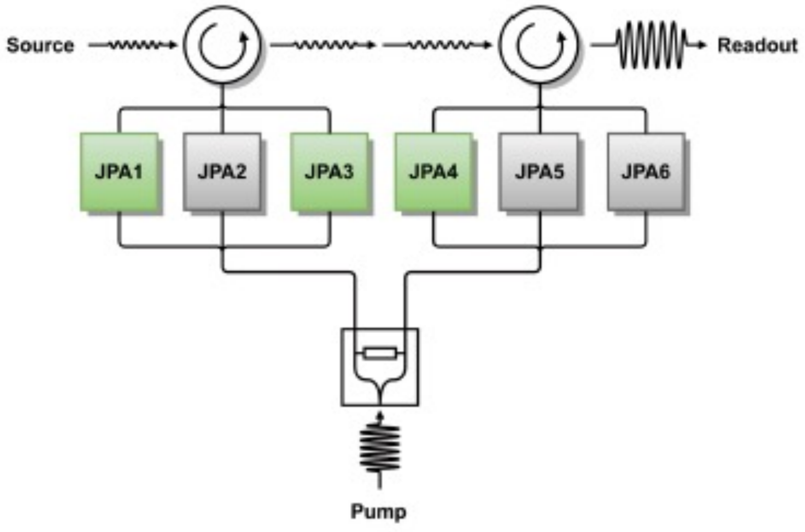


Chips designed and manufactured in Univ. of Tokyo (Arjan van Loo)
Packaging and shielding designed by Sergey Uchaikin (CAPP)

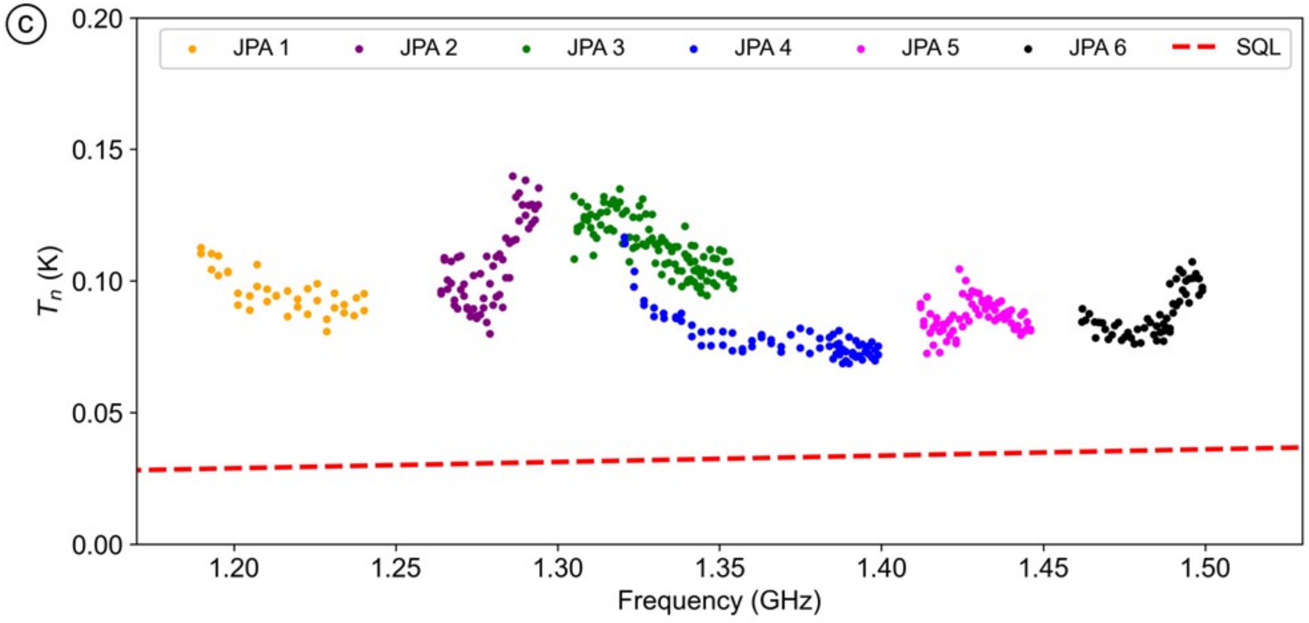
CAPP
Center for Axion and Precision Physics Research

CAPP-MAX, JPA-bundle development testing
Added system noise (JPA+ HEMT noise).
Chips by Tokyo (Nakamura et al.)
Development at CAPP:
Sergey Uchaikin et al.





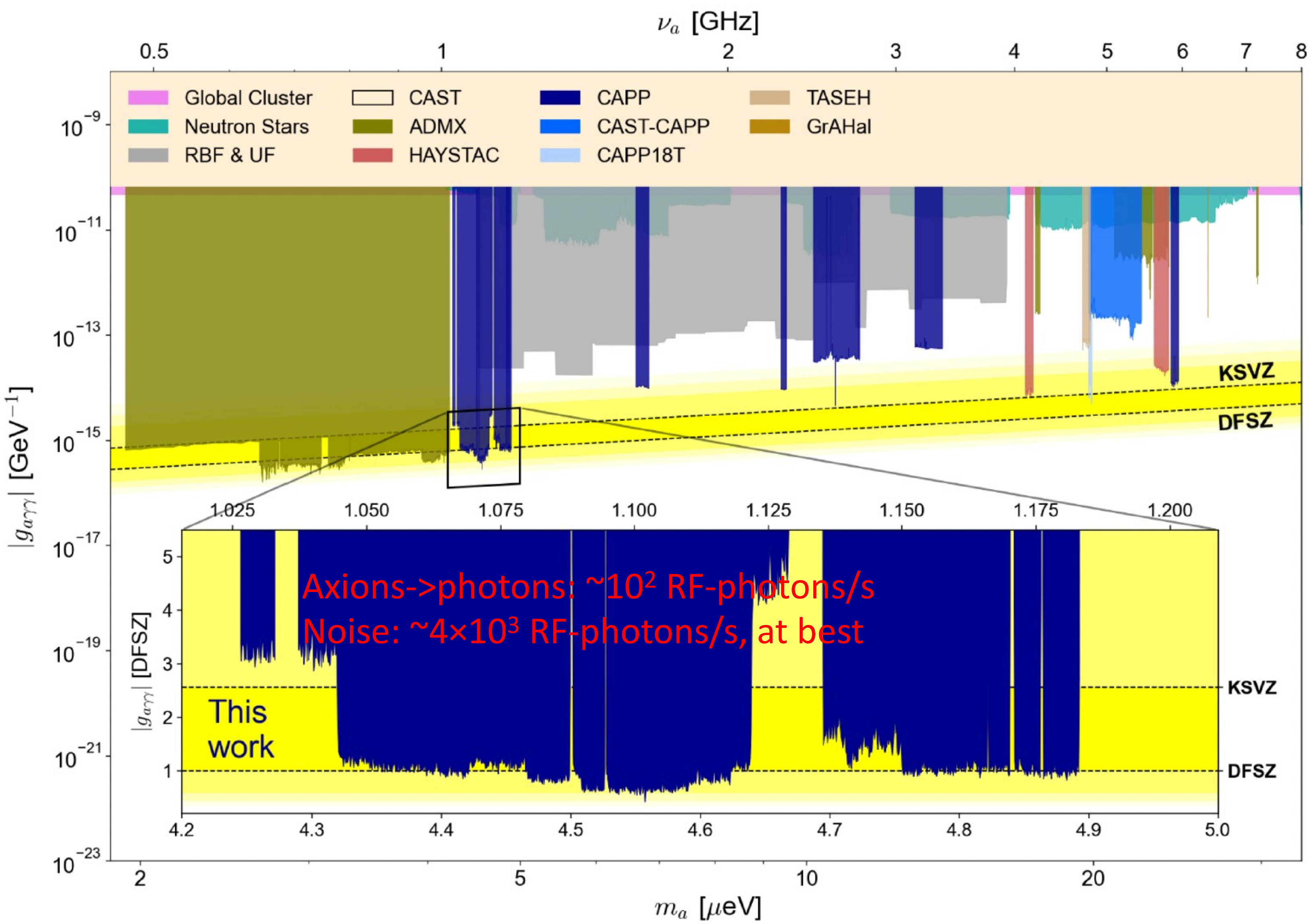
(b)



Combining JPAs to achieve high sensitivity in 1.2 - 1.5 GHz, running at low temperature <30mK

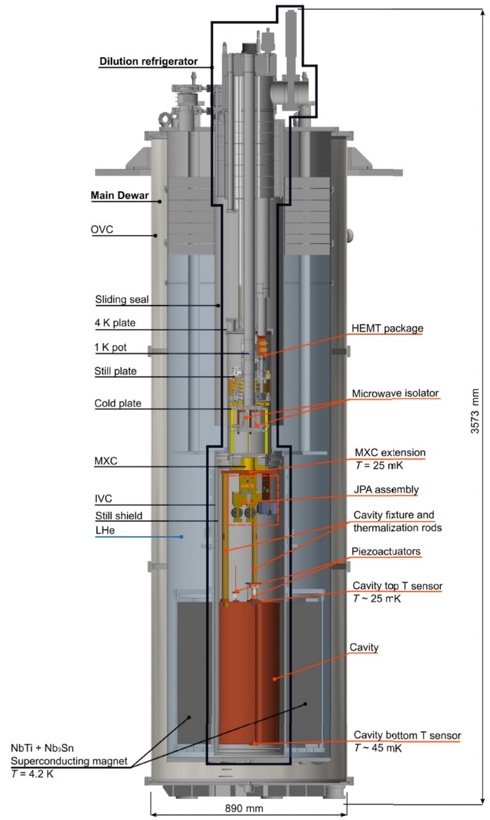
IBS-CAPP at DFSZ sensitivity, scanning 1-4 GHz

SAEBYEOK AHN *et al.* PHYS. REV. X **14,** 031023 (2024)



S. Ahn et al., PRX (2024) from CAPP.
A 32 page reference paper on how to achieve DFSZ sensitivity.

SAEBYEOK AHN *et al.* PHYS. REV. X **14,** 031023 (2024)



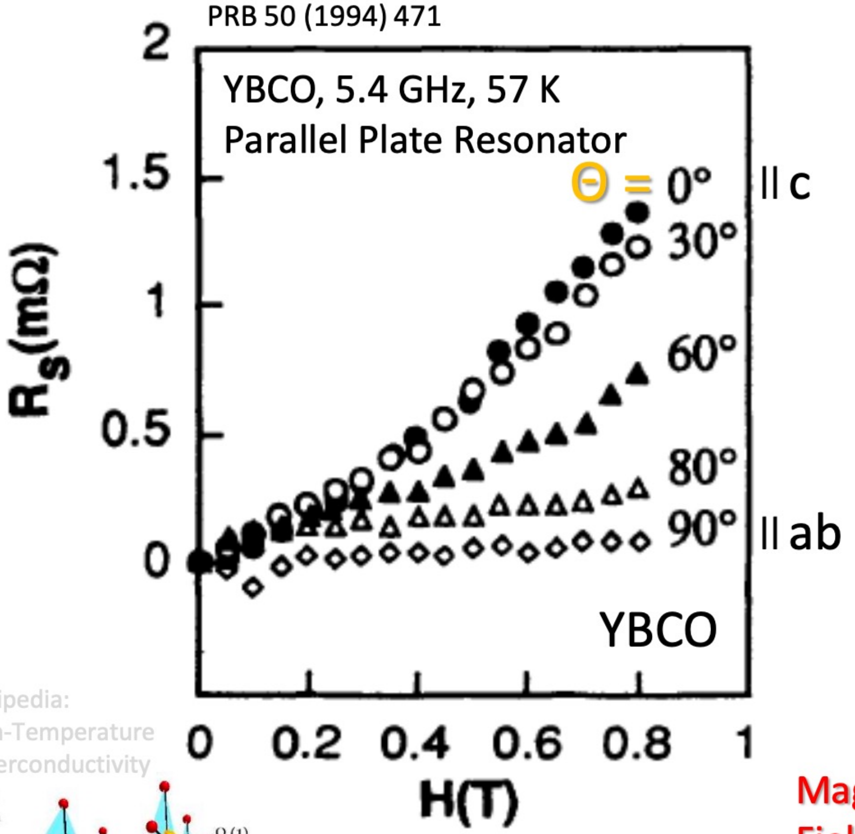
The best JPAs today

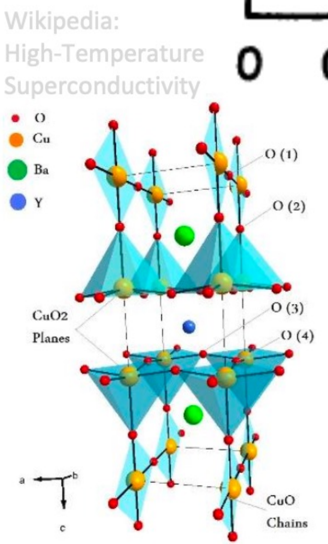
- Their average noise is between 3-5 times the quantum noise level
- Their frequency BW is limited, and they are labor intensive
- Require < 50mK cooling for best performance (at CAPP we had a best physical temp. ~22mK, with more common 25-40mK). The total system noise was ~220mK, requiring >100 s of integration time over the axion BW.

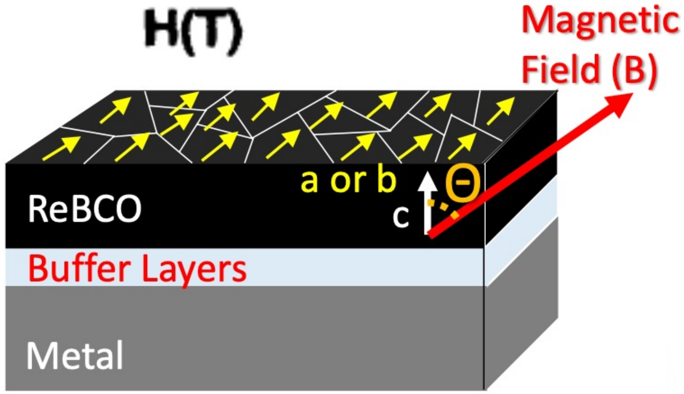
Cavities made of High Temperature Superconducting (HTS) tapes

Biaxially Textured ReBCO Tape

Danho Ahn's slide

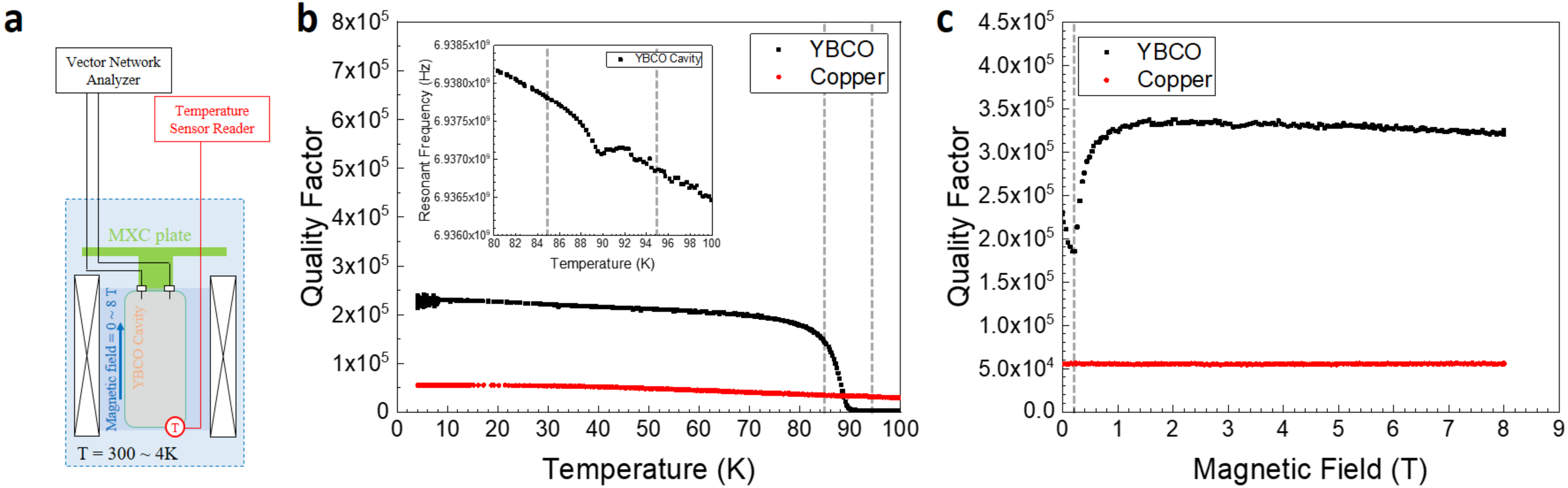






- ➢ Biaxially-Textured ReBCO films have anisotropy of surface resistance due to their crystal structure.
- ➢ The surface resistance of a film is maximized when the c axis of a crystal and the direction of an external magnetic field is parallel to each other.
- ➢ Directions of a ReBCO crystal should be considered to design a cavity.

HTS superconducting cavity in large B-field!



First and best in the world!

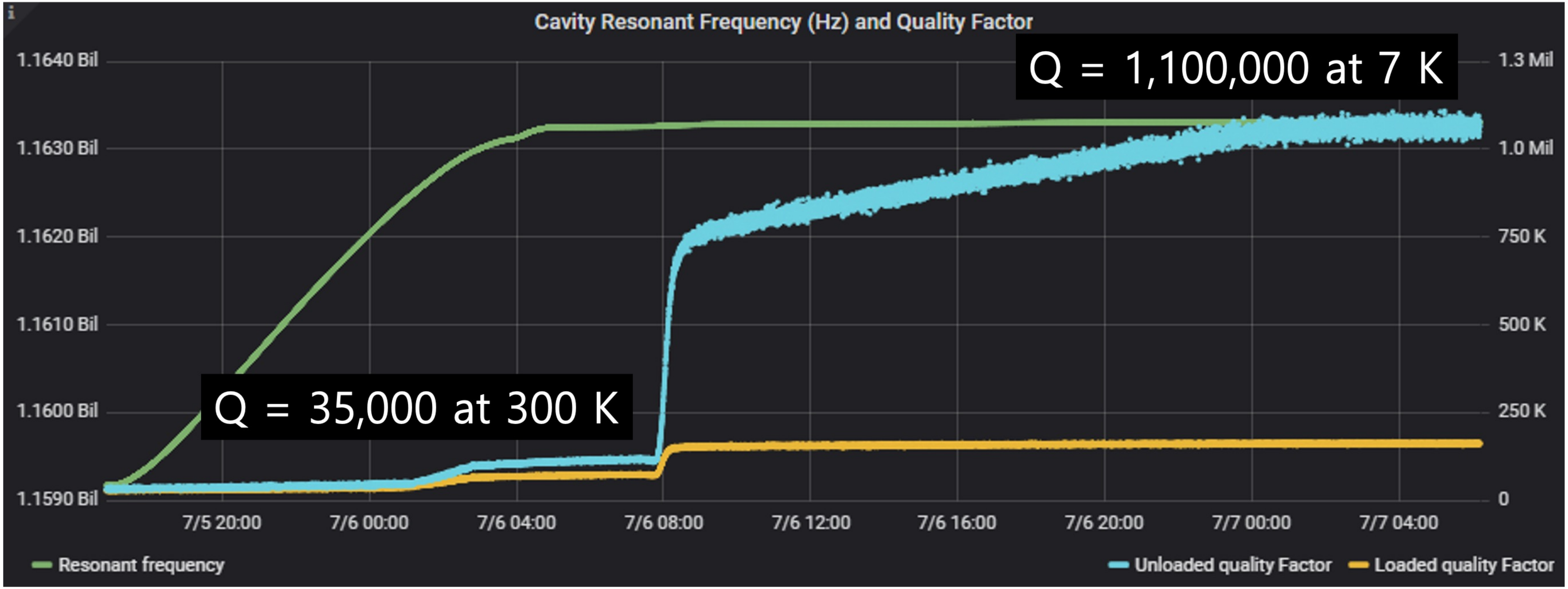
Phys. Rev. Applied **17**, L061005 – Published 28 June 2022

CAPP summer 2024, unique achievement, 34 liter cavity!

Full-HTS-ULC fabrication process

RF measurement w/ HTS tuning rod

Jiwon Lee's slide



Institute for Basic Science, 2011: Major Investment to Basic Sciences in South Korea.

- IBS-CAPP (est. 2013) scanned at DFSZ sensitivity for axions over 1 GHz in 2022, first time in the world.

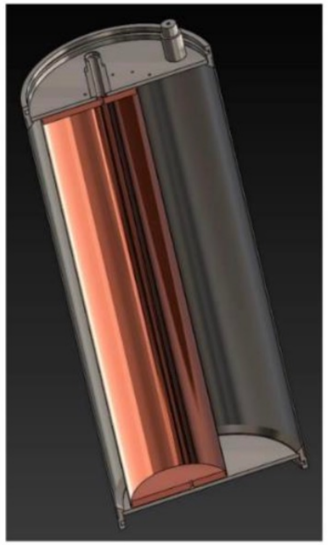
- Since summer 2024, a 34liter HTS cavity in 12T, with better than DFSZ sensitivity and able for >3MHz/day scanning rate.

- IBS-CAPP is now operating under another name: IBS-DMAG (Dark Matter Axion Group), under the leadership of SungWoo Youn

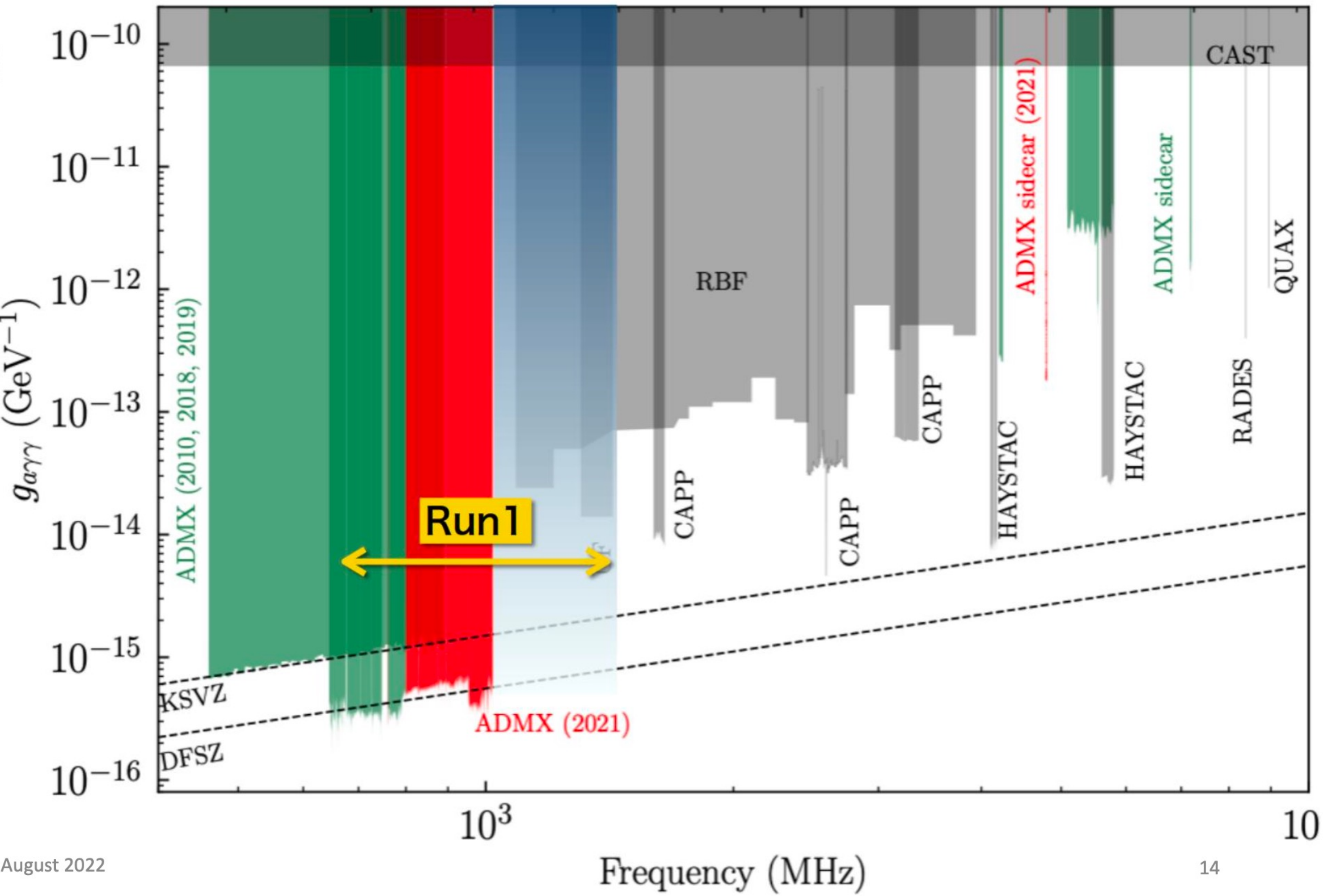
Photo: KAIST Munji Campus, January 2023

ADMX plan

Future Plans



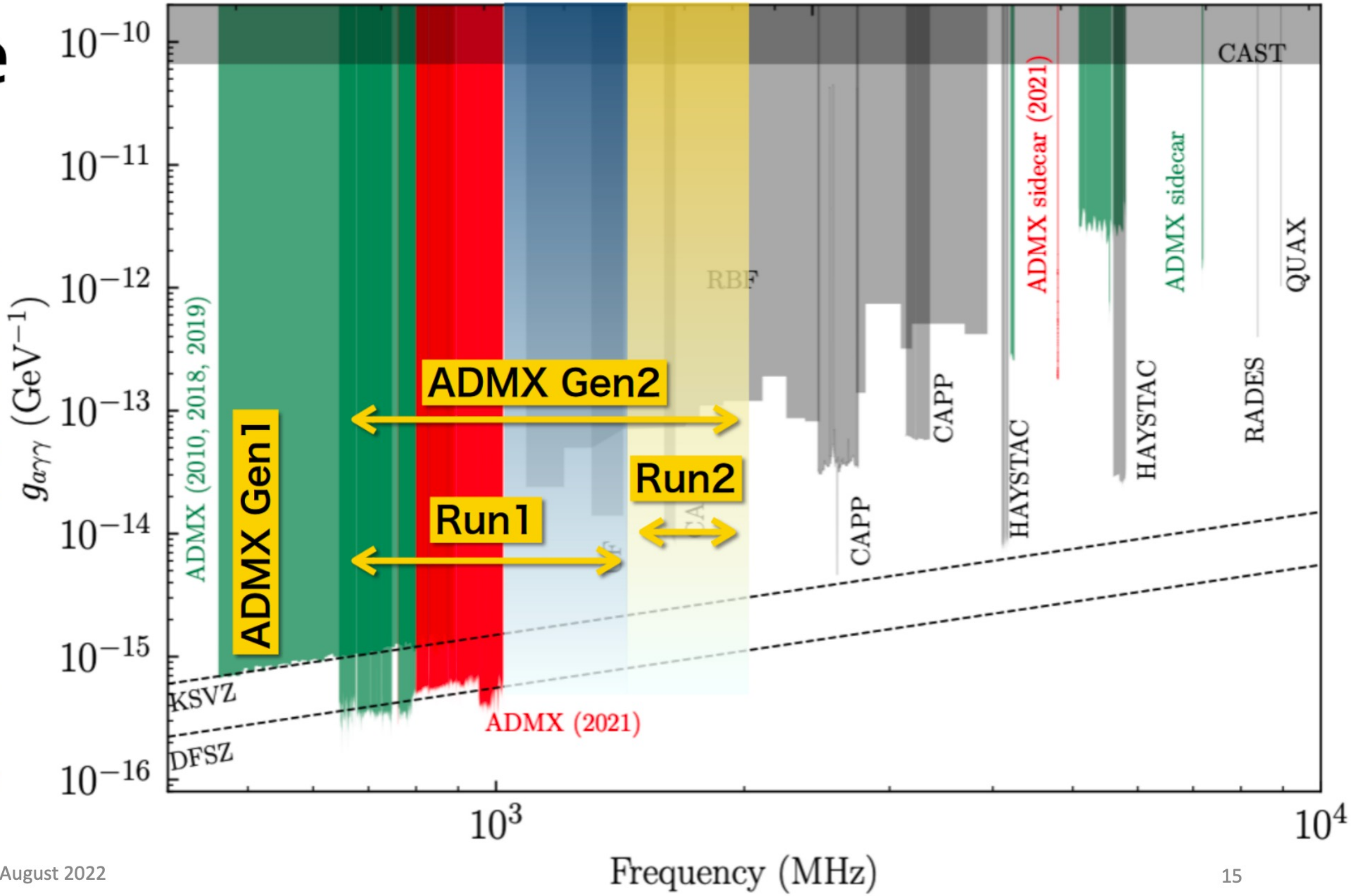
Bigger tuning rod



ADMX plan

Future Plans

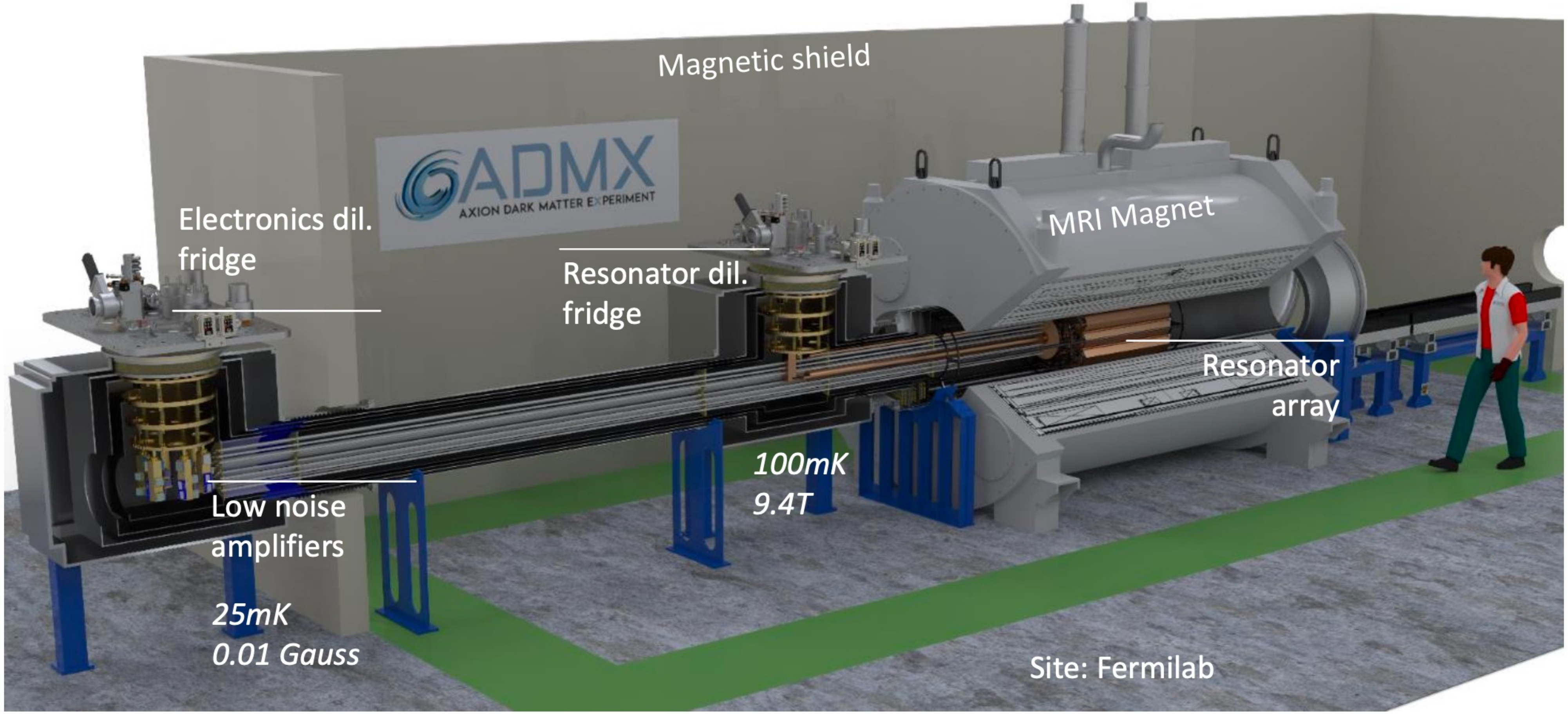
4-cavity array



ADMX: Rybka, August 2022

ADMX-EFR – Design Overview

Large-volume MRI magnet moved to Fermilab



~ 5 × scan speed of current ADMX

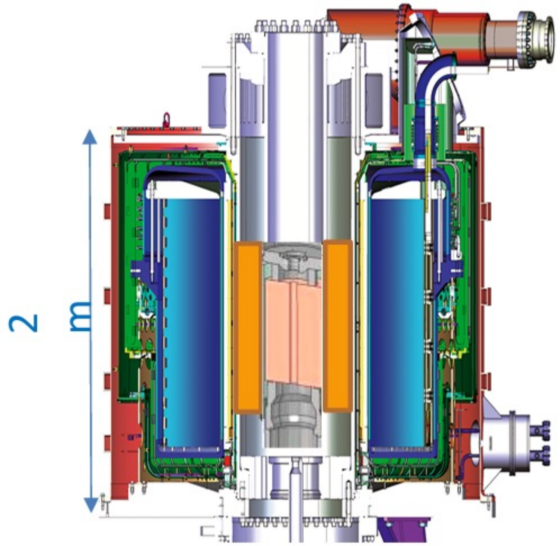
Grenoble Axion Haloscope and CAPP (~500 *l* cavity)

GrAHal
Grenoble Axion Haloscopes

GrAHal project

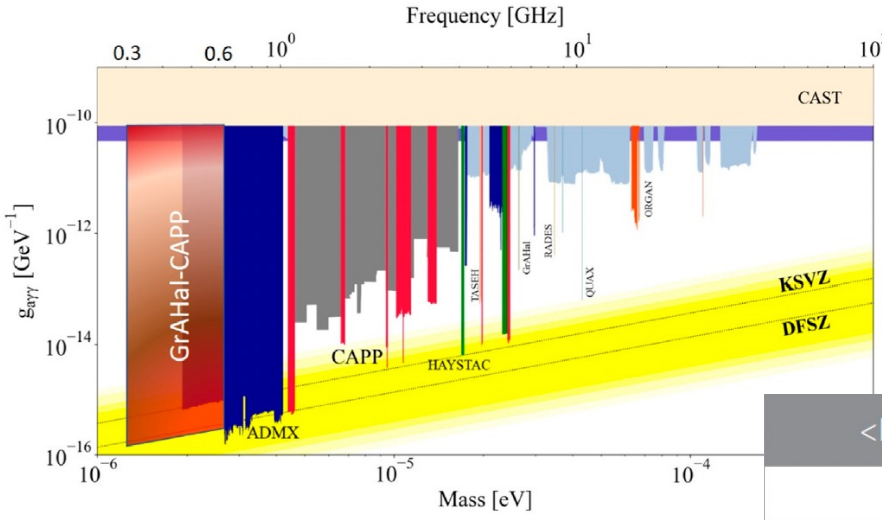
43+T Grenoble Modular Hybrid Magnet

LNCMI



Field	Warm dia.	RF-cavity dia.*	Frequency TM010	Height**
43 T	34 mm	20/12/8 mm	11-29 GHz	157 mm
40 T	50 mm	34/26/20 mm	5-11 GHz	157 mm
27 T	170 mm	86 mm	2.67 GHz	315 mm
17.5 T	375 mm	291 mm	0.79 GHz	484 mm
9 T	812 mm	675 mm	0.34 GHz	1400 mm

First target 300-600 MHz axion frequency.



- modular magnet is adapted to different frequencies/cavity designs for axion (GW) searches

e.g. : - 27T / 86mm → QUAX dielectric cavity

- 9T/675mm SC outsert → « low » frequency Sikivie cavity; « high » frequency metamaterial cavity

$\langle B^2V \rangle$ at 9 T central field	Q at 4.4 K	C_{010}	Noise T (K)	$g_{A\gamma\gamma}$
34.4 T^2 m^3	1–2 10^5	0.63–0.69	1.6	DFSZ

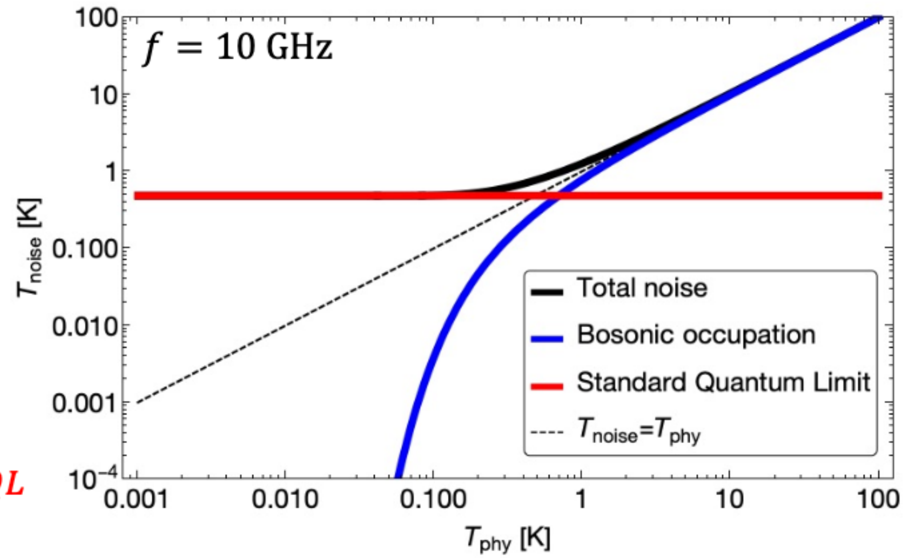
Equivalent noise temperature

Slide by SungWoo Youn

Noise contributions

$$T_{sys} = \frac{hf}{k_B}\left(\frac{1}{\exp\left[\frac{hf}{k_B T_{phy}}\right]-1} + \frac{1}{2} + \frac{G^2-1}{2G^2}\right)$$

- Thermal noise: bosonic occupation
- Zero-point fluctuations
- Minimum added noise



Standard quantum limit (SQL)

- Unavoidable limit by linear amplifiers

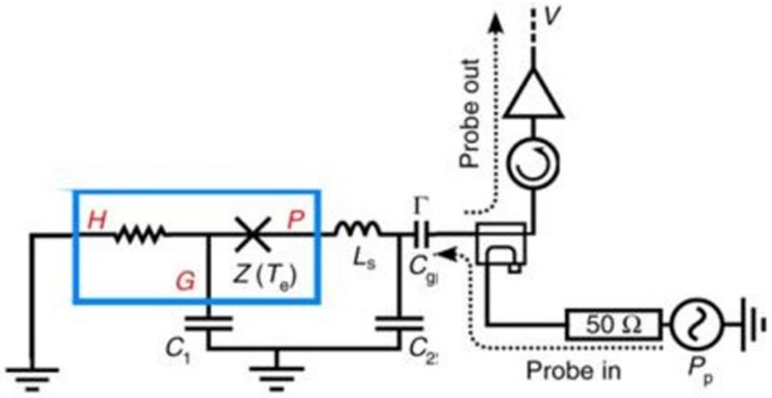
$$T_{sys} \geq \frac{hf}{k_B}\left(\frac{1}{2} + \frac{G^2-1}{2G^2}\right) \gtrsim \frac{hf}{k_B} \equiv T_{SQL}$$

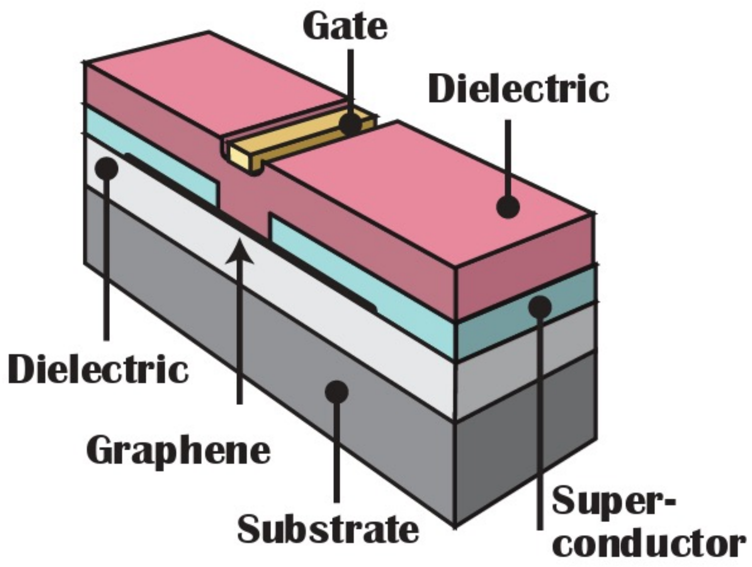
- Predominant at high frequencies

The uncertainty principle limits the lowest equivalent electronic noise of the system (quantum noise limited amplifiers). Single photon detectors (in blue) would be perfect, but they are still …far away from competing (however, see next).

Single RF-photon detector!

- A dream come true:
  - Lescanne et al., PRX (2020)
  - Albertinale et al., Nature (2021)
  - Wang et al., Nature (2023)
- Qubits or bolometers combined with HTS cavities pave the path to the high frequency. It’s getting very close to a major running system. See also yesterday’s talk by Klaara Viisanen





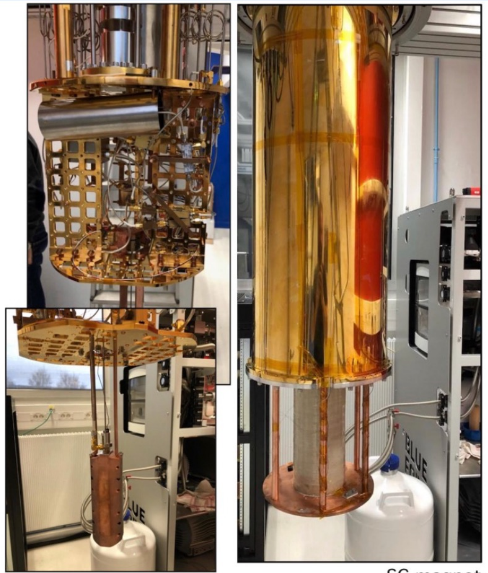
Nature 586, 47 (2020)

- Graphene bolometers based on JoFETs

QUAX experiment in Italy

Significant progress in single photon detection

Single Photon Detection – First Test @ Saclay

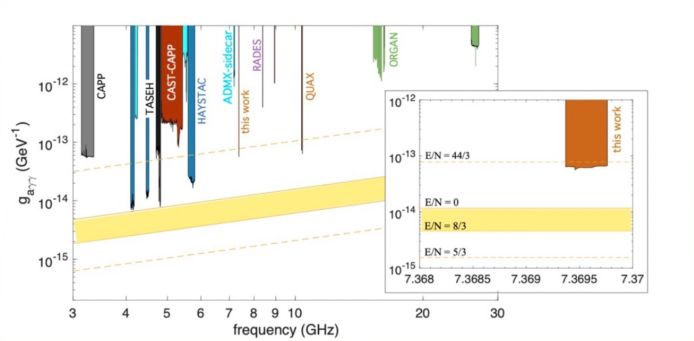


SMPD (top) and cavity

SC magnet

- hybrid (normal-superconducting) cavity 7.37 GHz, tunable, $Q_0 = 9 \times 10^5$
- T=14 mK delfridge base temperature @ Quantronics lab (CEA, Saclay)
- 2 T-field
- triplet of rods controlled by a nanopositioner mounted at the MC stage to probe for different axion masses
- passive protection by the B-field for SMPD and TWPA

- Developed a dedicated protocol
- Dark count at the 100 Hz level
- System stability up to 10 minutes



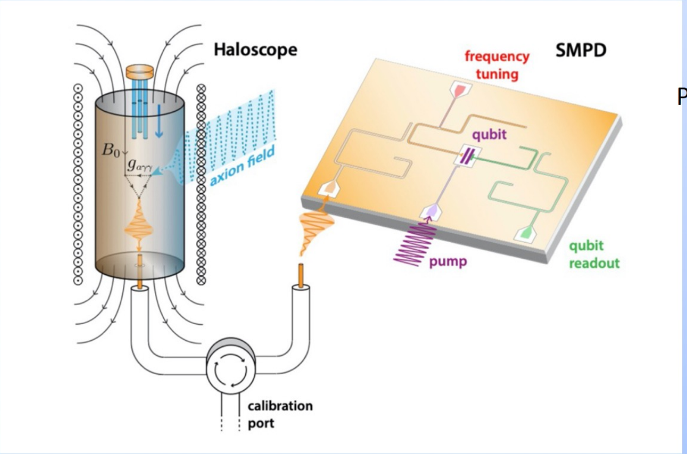
https://arxiv.org/abs/2403.02321

20 Times faster then SQL based Amplifier with a Dark Count @ 10 Hz (new Devices) 100

Next Generation Haloscope – Single Photon Detection

Joint effort between QUAX (LNL, PD), Padova Dept. of Excellence, SQMS, Quantronics Group Saclay

Single Microwave Photon Detector (SMPD) as haloscope receiver



Linear amplifier irreducible limit
Standard Quantum Limit

$$P_{\mathrm{SQL}} = h\nu_a\sqrt{\Delta\nu_a/t}$$

$$\mathrm{SNR}_{\mathrm{SQL}} = \frac{P_a}{h\nu_a}\sqrt{\frac{t}{\Delta\nu_a}}$$

Photon Counter PC limited by **dark count** Γ_{DC} rate and **efficiency** η

$$\mathrm{SNR}_{\mathrm{PC}} \approx \frac{\eta P_a}{h\nu_a}\sqrt{\frac{t}{\Gamma_{\mathrm{dc}}}}$$

Improvement in scanning speed with SMPD

$$\eta^2\frac{\Delta\nu_a}{\Gamma_{\mathrm{dc}}}$$

Cresini et al., PRL 124, 171801 (2020)
Braggio et al., PRX 15, 021031 (2025)

From Lattice QCD and requiring axions as dark matter the preferred mass range is: 40-180 μeV

M. Buschmann et al., Dark matter from axion strings with adaptive mesh refinement, Nature Commun. 13, 1049 (2022), arXiv:2108.05368 [hep-ph].

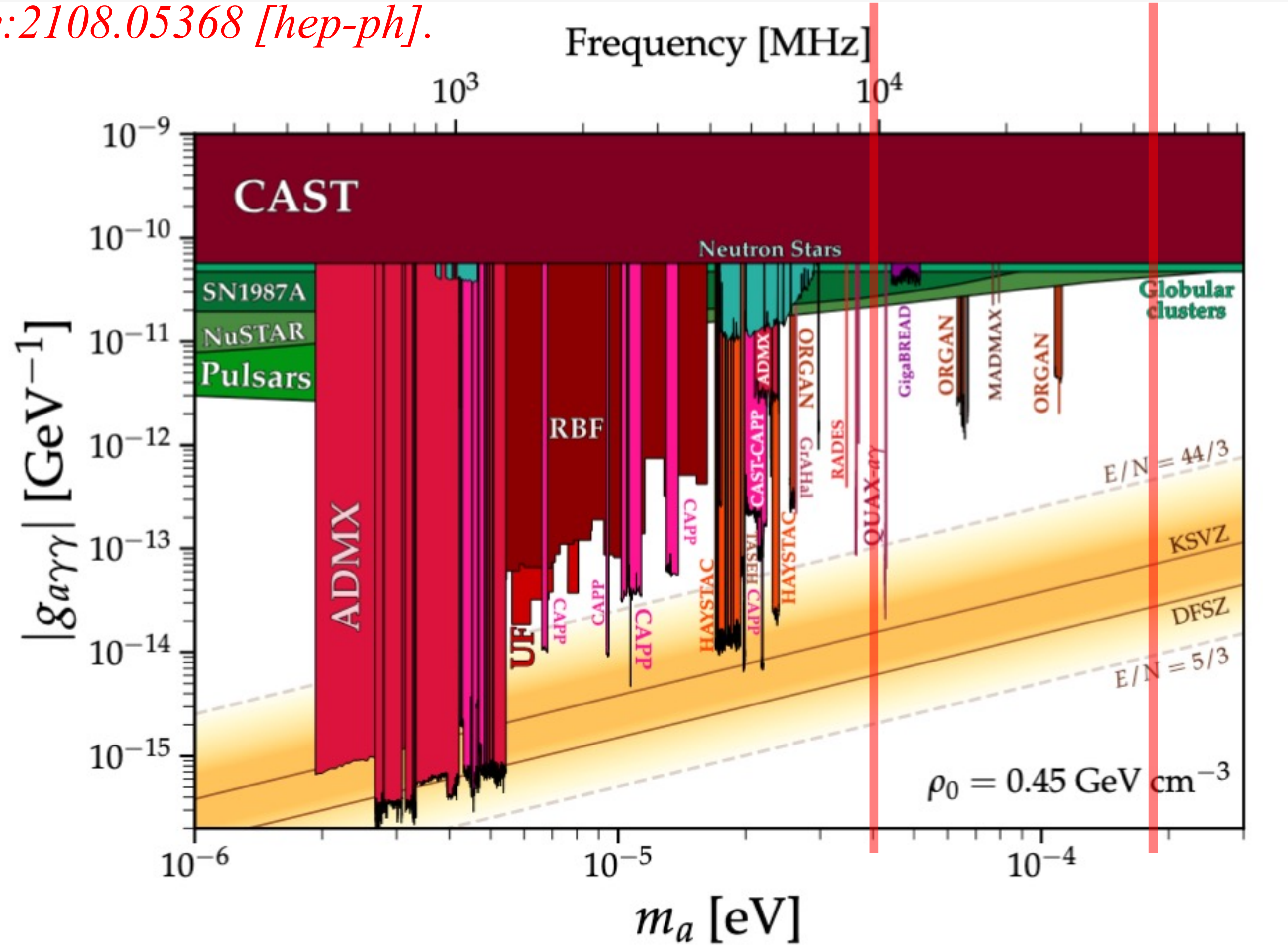
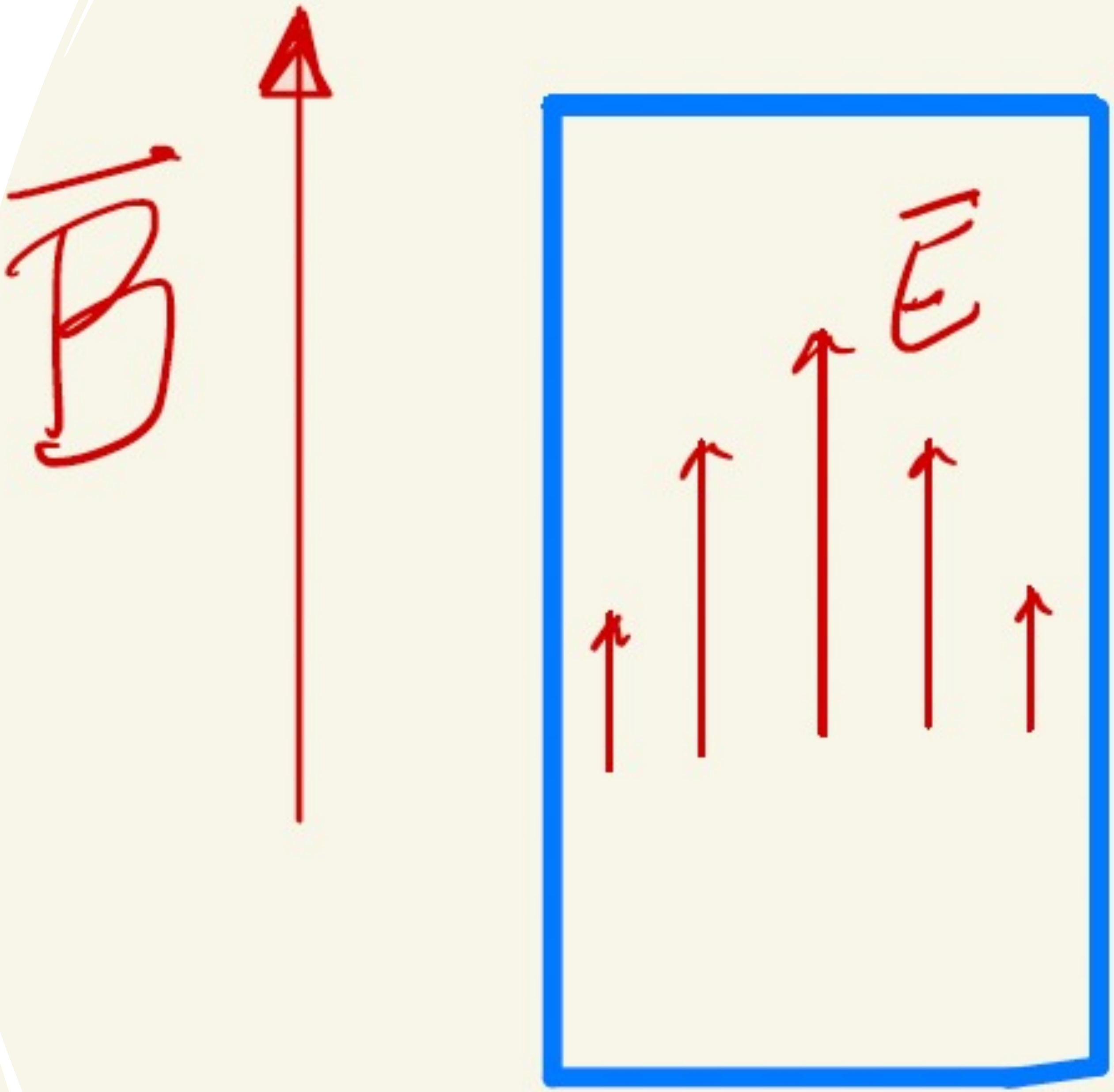


FIG. 1: The current status of the axion to two photon coupling in the mass range 1-300 μeV, corresponding to the frequency range 0.2-70 GHz (from Ref. [23]). CARAMEL aims to facilitate probing the frequency range of 0.5-50 GHz, or ~ (2-200) μeV, with better than DFSZ sensitivity within the next five years. CARAMEL can potentially cover the preferred post-inflationary parameter space, corresponding to 40-180 μeV [17], at better than DFSZ sensitivity, using presently available technical capabilities.

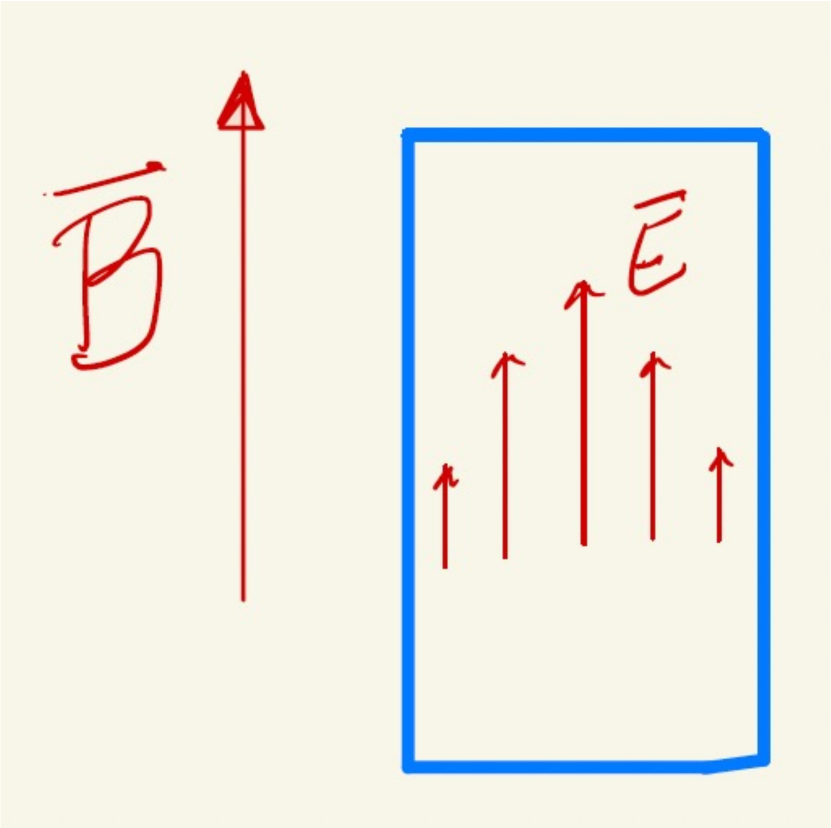
Prospects of scanning the whole axion frequency range

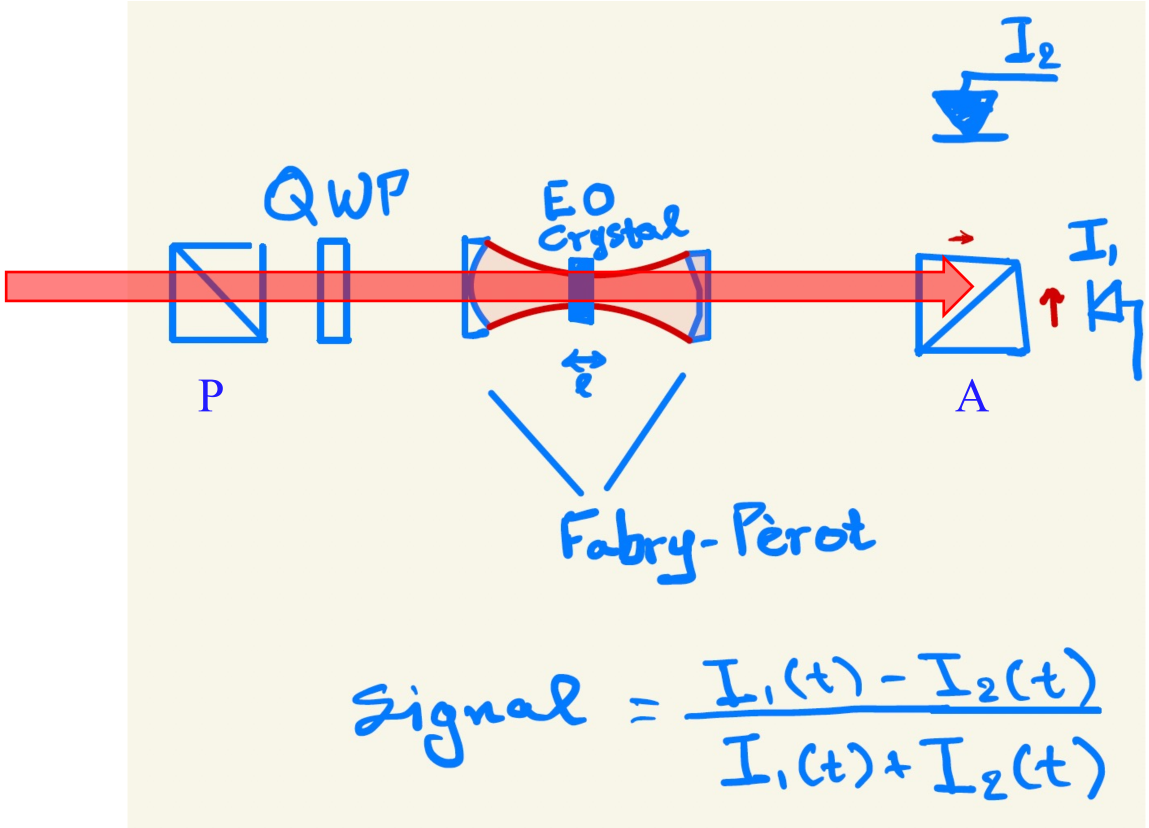
- With current methods we are still looking at a few decades before scanning the whole viable axion frequency.
- With CARAMEL we aim to achieve DFSZ sensitivity in the 40-180 μeV (10-45 GHz) range with a (nominal) year’s running time.

Electro optic detection of axion induced electric fields in microwave cavities

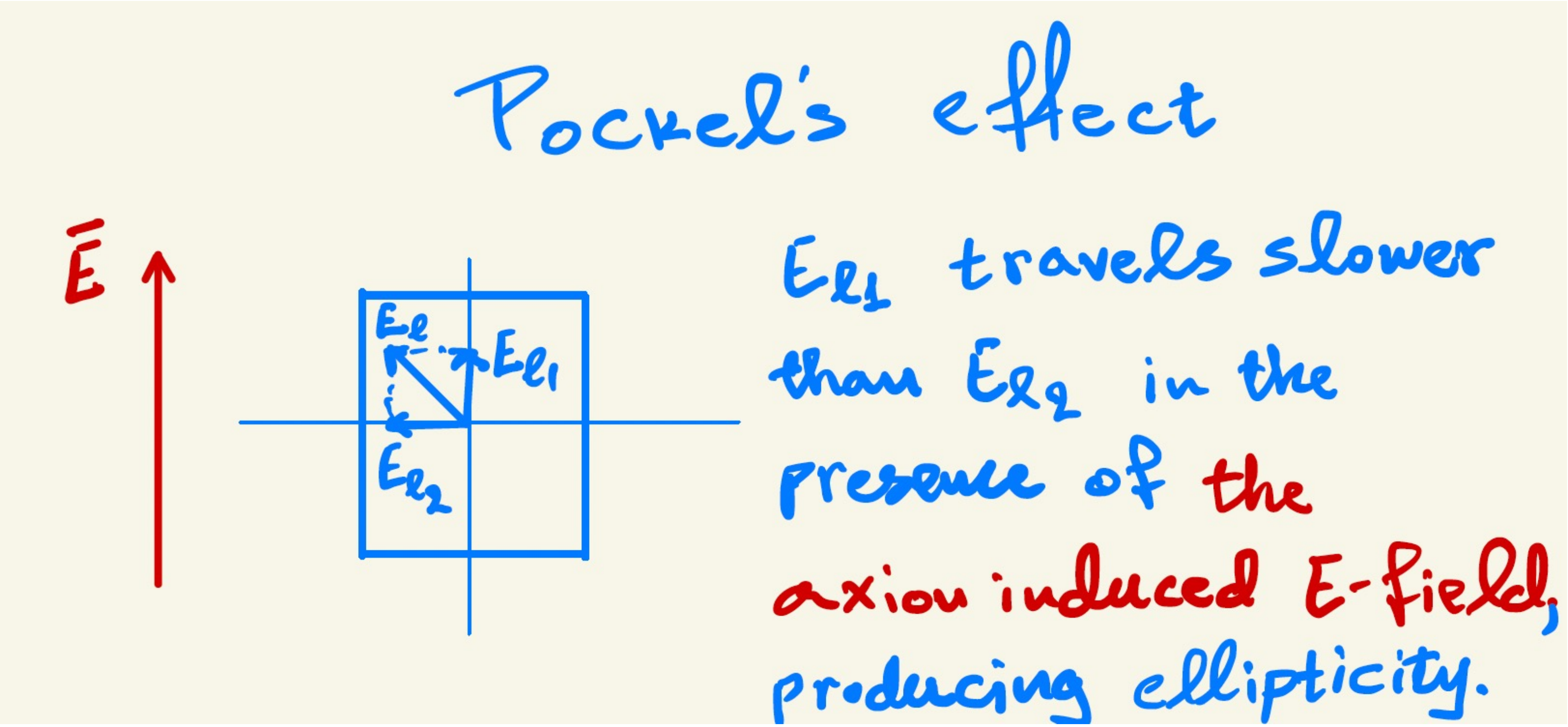


Electro optic detection of axion induced electric fields in microwave cavities





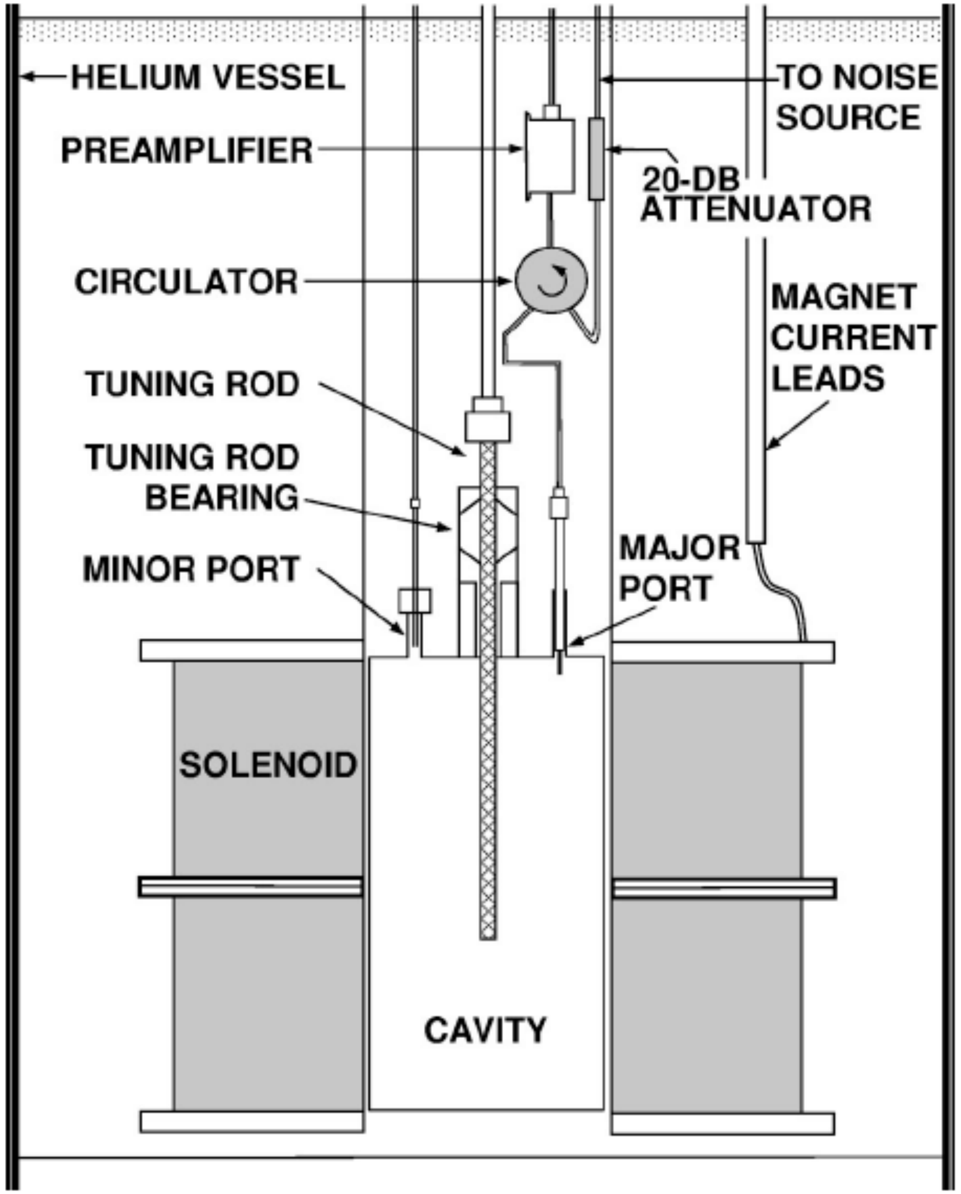
Electro optic detection of axion induced electric fields in microwave cavities



$$\Delta\phi = \phi_x - \phi_y = \frac{2\pi}{\lambda} n^3 r_{33} E L.$$

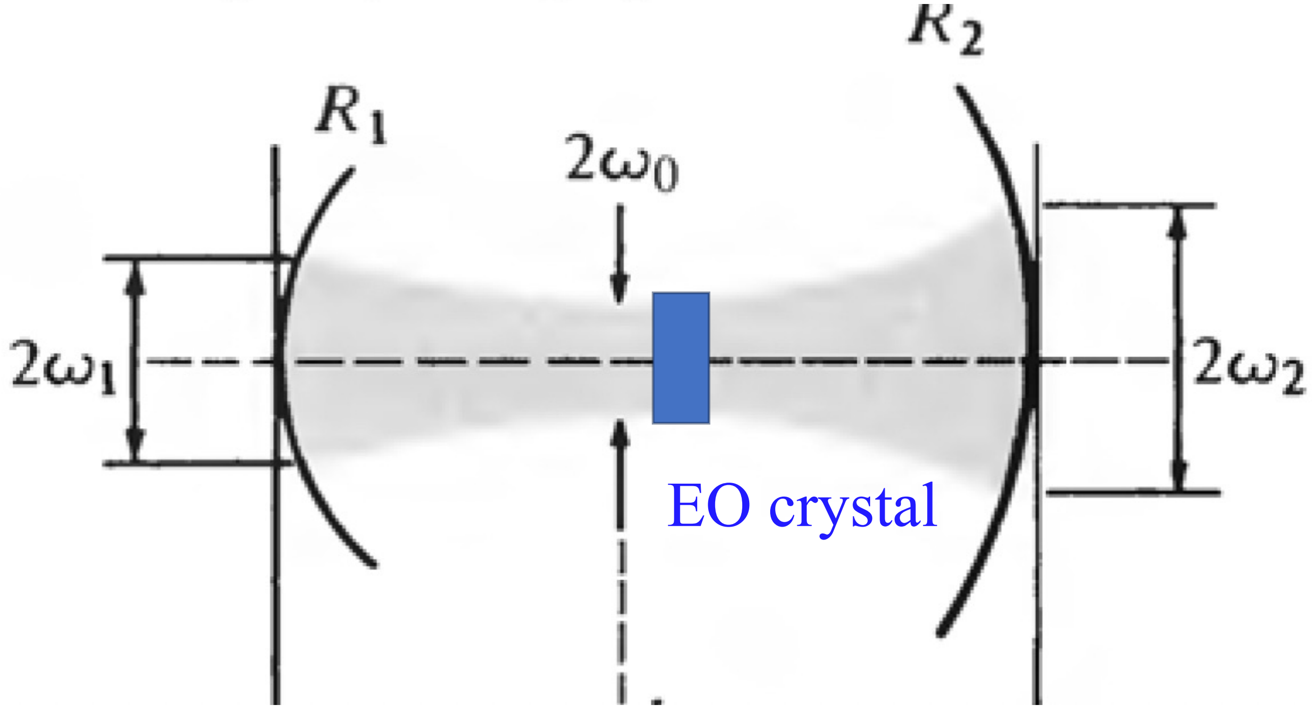
For $LiNbO_3$ crystal:
n=2.2, r_{33} = 3.1 × 10^{-11} m/V

Electro optic (EO) readout using a Fabry Perot resonator plus heterodyning (probing, PRD 107, 103005 (2023)).



Parameter	Value
Laser Power	10 mW
Laser Wavelength	1064 nm
RF Probe Power	2 nW
Microwave Cavity Quality Factor Q_c	10^4
Axion-to-Photon Reference Power P_a ($Q_c = 10^4$)	10^{-23} W
Microwave Cavity Volume	3.7 L
Fabry-Pérot Finesse $\mathcal{F}$	10^4
EO Crystal ($LiNbO_3$) Thickness L	3 mm

TABLE I: Benchmark parameters assumed in this work, for the $\nu_a \sim O(10\ \text{GHz})$ regime.



EO measurement using a Fabry-Perot resonator alone

The basis of our proposal is the use of the EO effect, where an electric field $E \equiv |\vec{E}|$ leads to induced ellipticity ψ in a laser beam of wavelength λ (Pockels effect [44, 45]). We have

$$\psi = \frac{\pi}{\lambda} n^3 r_{ij} \, E \, L \,, \tag{1}$$

where n is refractive index of the EO crystal, r_{ij} is assumed to be the largest element of the EO coefficient tensor, and L is the length of the crystal through which the laser propagates.

$$U_E = \frac{1}{2}\epsilon_0 V E_a^2 = \frac{U}{2} = \frac{P_a Q_c}{2\omega}, \tag{6}$$

where E_a is the root-mean-square electric field, $\epsilon_0 = 8.85 \times 10^{-12}$ F/m is the vacuum permittivity, and V is the cavity volume. Solving for E_a we get

$$E_a = \sqrt{\frac{P_a Q_c}{\omega \epsilon_0 V}}\,, \tag{7}$$

We will consider using lithium niobate, $LiNbO_3$, of size $L = 3$ mm, as our EO crystal, for which $n \approx 2.2$ and $r_{33} \approx 3.1 \times 10^{-11}$ m/V. Let us take $f = 10$ GHz as a representative value. We will consider the benchmark values $P_a = 10^{-23}$ W and $Q_c = 10^4$ for the chosen value of f above. From Eqs.(1) and (7), we get $E_a \approx 7.0 \times 10^{-9}$ V/m and $\psi_a \approx 2 \times 10^{-14}$ rad.

1. Axion induced electric field oscillation amplitude (for Q_c=10^4): E_a=7nV/m.
2. Ellipticity induced for a single pass $\psi \sim 2\times10^{-14}$ rad
3. With a Fabry-Perot and 10^4 finesse $\psi_{FP} \sim 1.3\times10^{-10}$ rad. Laser shot noise: $\psi_{LSN} \sim 3.5\times10^{-9}$ rad (3s integration time)
4. Not quite enough. We need to do better…

EO measurement using a Fabry-Perot plus heterodyning (probing)

Axion field at 10 GHz is coherent for ~0.1ms, the laser noise is incoherent.

Next, we will examine implementing the probing method to provide a feasible detection approach, without FP enhancement. We will consider an injected RF power $P = 2\,\mathrm{nW} = 2 \times 10^{-9}$ W. The electric field amplitude, for $\omega = 2\pi \times 10^{10}$ rad Hz, is:

$$E_{\mathrm{probe}} = \sqrt{\frac{Q_c P}{\epsilon_0 V \omega}} \approx 0.1\,\mathrm{V/m} \qquad (13)$$

In the probing method, we are interested in detecting the fluctuations of the ellipticity, which are enhanced by the RF injected power. To see this, we note that the total electric field in the cavity is given by

$$E(t) = E_{\mathrm{probe}} \cos(\omega t) + E_a \cos(\omega t + \phi(t)), \qquad (14)$$

where $\phi(t)$ is the time-dependent relative phase between the two fields.

The axion field is not perfectly monochromatic; it has a finite spectral width $\Delta\nu_a \sim 10^{-6}\nu$ due to the virialized velocity dispersion of dark matter in the galactic halo. At $\nu = 10\,\mathrm{GHz}$, this corresponds to $\Delta\nu_a \sim 10\mathrm{kHz}$ and a coherence time of

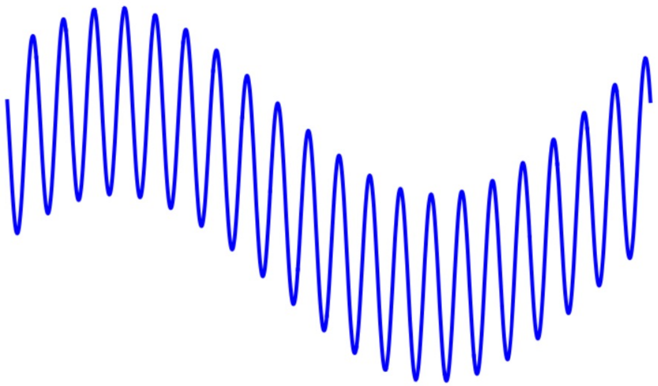
$$\tau_a \sim \frac{1}{\Delta\nu_a} \sim 0.1\,\mathrm{ms}. \qquad (15)$$

Over timescales shorter than τ_a, the axion field behaves like a coherent wave with a well-defined phase. Over longer timescales, this phase $\phi(t)$ drifts randomly, reflecting the stochastic nature of the axion field.

In the probing method, one is interested in measuring the variance of the ellipticity

$$\langle \psi^2 \rangle \propto \frac{1}{2}\left[E_{\mathrm{probe}}^2 + E_a^2 + 2E_{\mathrm{probe}} E_a \langle \cos(\phi(t)) \rangle\right], \qquad (16)$$

where $\langle \cos(\phi(t)) \rangle$ vanishes over many coherence times, but the variance of the fluctuations is nonzero. To cap-



Heterodyne-variance method, Omarov, Jeong, YkS: PRD107, 103005 (2023)

Injecting photons into the microwave cavity can enhance the axion detection rate

System Noise Temperature

Adapted from Junu Jeong's slides

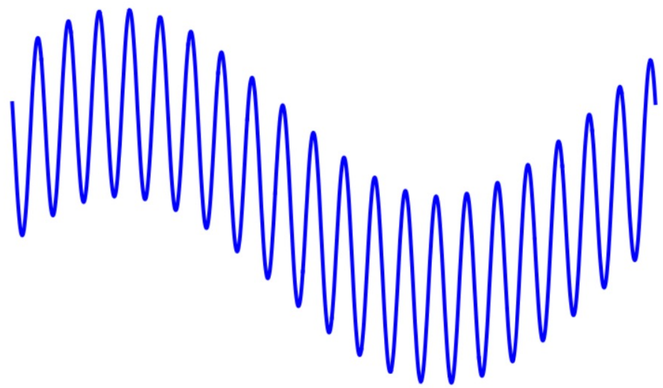
- **Noise Sources**

$$T_{\rm sys} = \boxed{T_{\rm thermal}} + \boxed{T_{\rm amplifier}} = \frac{hf}{k_B}\left(\frac{1}{\exp[hf/k_B T_{\rm phy}]-1}+\frac{1}{2}\right) + T_{\rm amplifier}$$

Shot noise (Randomness of Amplification)

Bosonic statistics + Zero-point fluctuation

Dilution Refrigerator sufficiently reduces $T_{\rm thermal}$ *down to the limit* $(0.5\,hf)$



- **Amplifier Noise** [1]

$$T_{\rm amplifier}^{\rm current\ best} \approx 1.2\,hf, \qquad T_{\rm amplifier}^{\rm limit} = 0.5\,hf$$

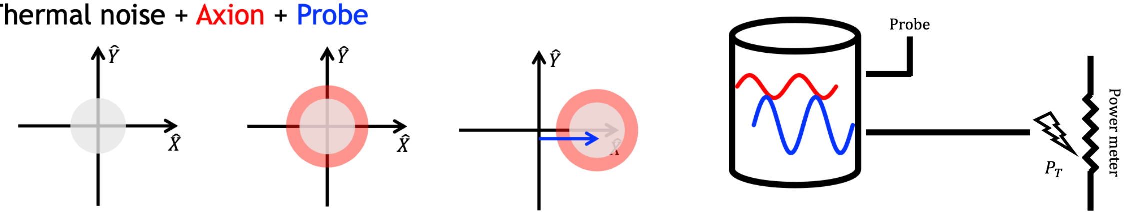
- **Heterodyne**

Mixing two frequencies

$$\propto \frac{1}{2}E_{\rm sig}^2 + \frac{1}{2}E_{\rm LO}^2 + 2E_{\rm sig}E_{\rm LO}\cos(\omega_{\rm sig}t+\varphi)\cos(\omega_{\rm LO}t)$$

Heterodyne haloscope

- **Assuming the axion and the probe are *the same frequency but random phase***
  - Thermal noise + Axion + Probe



⇒ Injecting the probe simply shifts the signal in IQ plane

⇒ It does not change the signal-to-noise ratio in IQ plane

Instead of the power detector, we propose to use the EO effect and a Fabry-Perot resonator

Heterodyne-variance method: PRD107, 103005 (2023)

Can always reach QNL performance even when the power detectors (bolometers) are noisy

Variance statistics

- **SNR of the variance estimator**

  Detector sampling rate: f_s

  Photon rate: $\dot{N} \equiv N \times f_s$

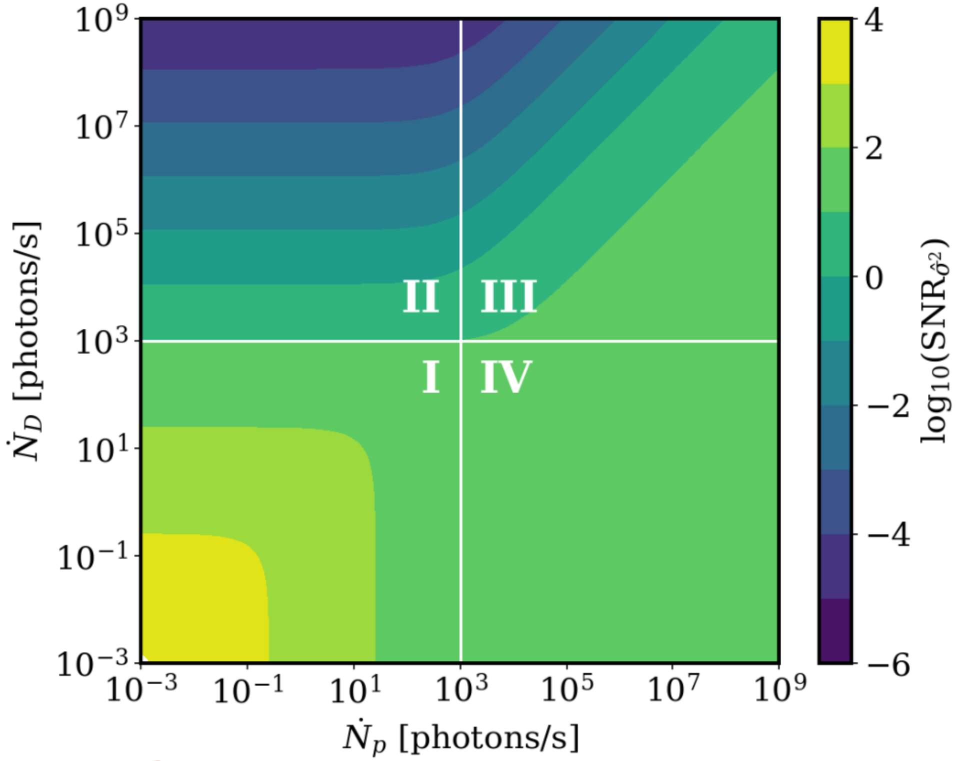
$$\mathrm{S/N}_{\sigma^2} \approx \frac{\dot{N}_s(1+\dot{N}_p/f_s)\sqrt{f_s \Delta t}}{(\dot{N}_D+\dot{N}_p)\sqrt{2+f_s/(\dot{N}_D+\dot{N}_p)}} \xrightarrow{\dot{N}_p \gg f_s} \frac{\dot{N}_s}{\sqrt{2f_s}}\sqrt{\Delta t}$$

- **Region I:** $\dot{N}_D < f_s,\ \dot{N}_p < f_s$
- **Region II:** $\dot{N}_D > f_s,\ \dot{N}_p < f_s$
- **Region III:** $\dot{N}_D > f_s,\ \dot{N}_p > f_s$

  Injecting probe increases the SNR, converging to $\dot{N}_D|_{eff} \rightarrow 2f_s$
- **Region IV:** $\dot{N}_D < f_s,\ \dot{N}_p > f_s$

  Injecting prboe reduces the SNR

Junu Jeong's slide



Next, we will examine implementing the probing method to provide a feasible detection approach, without FP enhancement. We will consider an injected RF power $P = 2\,\mathrm{nW} = 2\times10^{-9}$ W. The electric field amplitude, for $\omega = 2\pi\times10^{10}$ rad Hz, is:

$$E_{\rm probe} = \sqrt{\frac{Q_c P}{\epsilon_0 V \omega}} \approx 0.1\,\mathrm{V/m} \qquad (13)$$

Given the above discussion, the detected ellipticity scales with the geometric mean of the axion and probe electric fields:

$$\psi_{\rm probe} = \frac{\pi}{\lambda} n^3 r_{33} \sqrt{E_a E_{\rm probe}}\, L \qquad (17)$$

Substituting the above benchmark values, we find $\psi_{\rm probe} \approx 7.7\times10^{-11}$ rad. As before, if we employ a FP cavity with a finesse $\mathcal{F}$, we can enhance the signal

EO measurement using a Fabry-Perot plus heterodyning (probing)

1. Heterodyning (probing) enhances the axion signal by sqrt($E_{\rm probe}/E_a$)~3×10^3
2. The axion induced ellipticity is now ~ 5×10^{-7} rad at 10 GHz with 10kHz modulation.
3. We can see this in less than 3s.

$$\psi_{\rm probe} \to \left(\frac{2\mathcal{F}}{\pi}\right) \psi_{\rm probe}\,, \qquad (18)$$

which for $\mathcal{F} = 10^4$ will result in $\psi_{\rm probe} \approx 4.9\times10^{-7}$ rad.
Thus, the SNR for a 10 mW laser power and int
ing for 3 s, is :

$$\mathrm{SNR}_{\rm probe-FP} \approx \frac{(2\mathcal{F}/\pi)\psi_{\rm probe}}{\delta\psi_{\rm shot}} \approx \frac{4.9\times10^{-7}}{3.5\times10^{-9}} \approx 140 \qquad (19)$$

The dominant noise

1. Thermal and vacuum (quantum) induced noise.
2. (In the current experiments the dominant noise comes from the readout electronics)

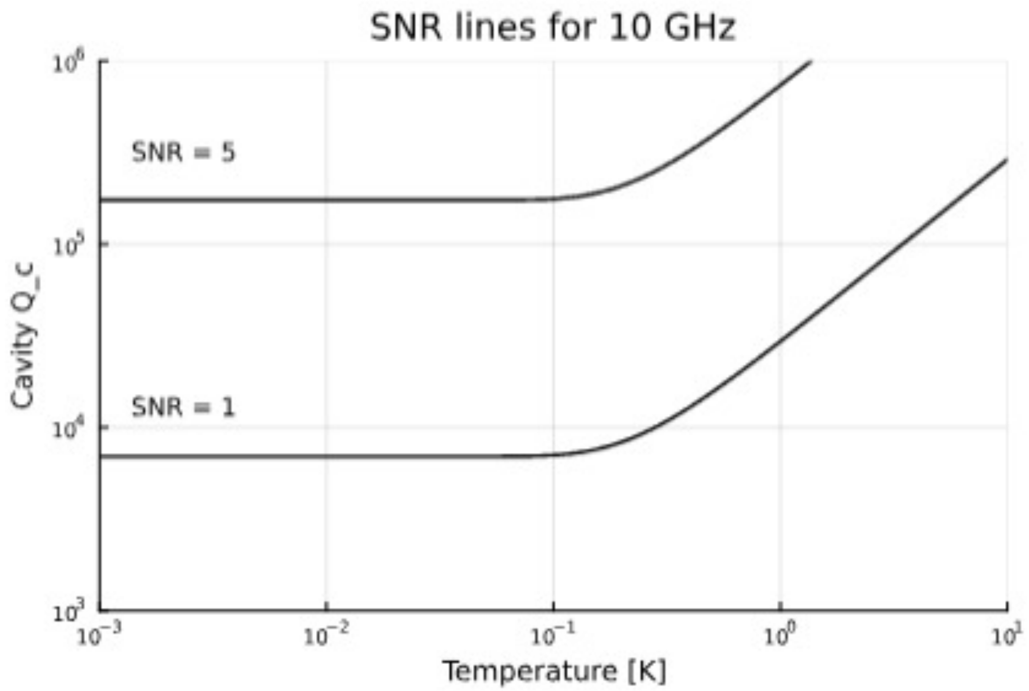


FIG. 2: Signal-to-noise ratio (SNR) as a function of Q_c and T at different operating frequencies. The transition from the quantum regime to the classical regime becomes apparent around 480 mK, where the thermal photon occupation number begins to exceed the vacuum (zero-point) contribution. The cavity volume is kept constant at 3.7 liters. The axion to photon conversion power is kept at 10^{-23} W assuming $Q_c = 10^4$, $t = 3$ s, and scaled appropriately for different cavity quality factor values; see Supplemental Material.

The axion-induced power is:

$$P_a = P_0 \, Q_{\rm red} , \tag{25}$$

where P_0 is a reference quantity and

$$Q_{\rm red} \equiv \frac{Q_c Q_a}{Q_c + Q_a} . \tag{26}$$

For our benchmark choices $P_0 = 10^{-27}$ W, for $Q_c = 10^4$.

$$\boxed{\mathrm{SNR}(t) = \sqrt{\frac{P_0 Q_{\rm red} t}{\pi \hbar\omega \coth(\frac{\hbar\omega}{2k_B T})}}} . \tag{29}$$

This expression smoothly interpolates between the quantum regime at low temperatures (where coth $\to$ 1) and the classical limit at high temperatures (where coth $\to \frac{2k_B T}{\hbar\omega}$).

Frequency dependence

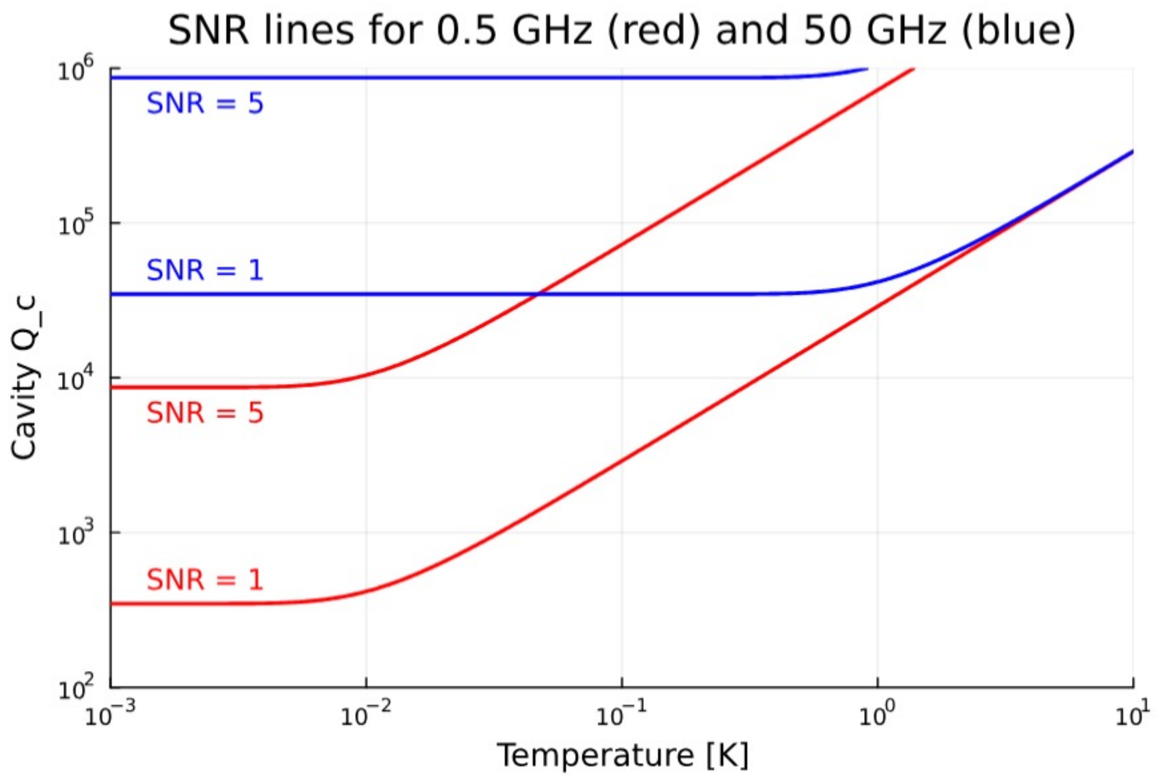


FIG. 3: Signal-to-noise ratio (SNR) as a function of Q_c and T at different operating frequencies. The transition from the quantum regime to the classical regime becomes apparent around 24 mK for 0.5 GHz (red), and 2.4 K for 50 GHz (blue), where the thermal photon occupation number begins to exceed the vacuum (zero-point) contribution. The cavity volume is kept constant at 3.7 liters. The axion to photon conversion power is kept at 10^{-23} W assuming $Q_c = 10^4$ and scaled appropriately for different cavity quality factor values; see text.

1. We can achieve DFSZ sensitivity even for 50 GHz for just 3s integration time per bin.

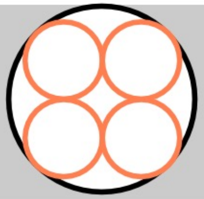
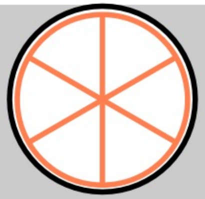
2. The frequency range shown includes the favorite range for after inflation PQ scale (10-45 GHz), Buschmann (2022).

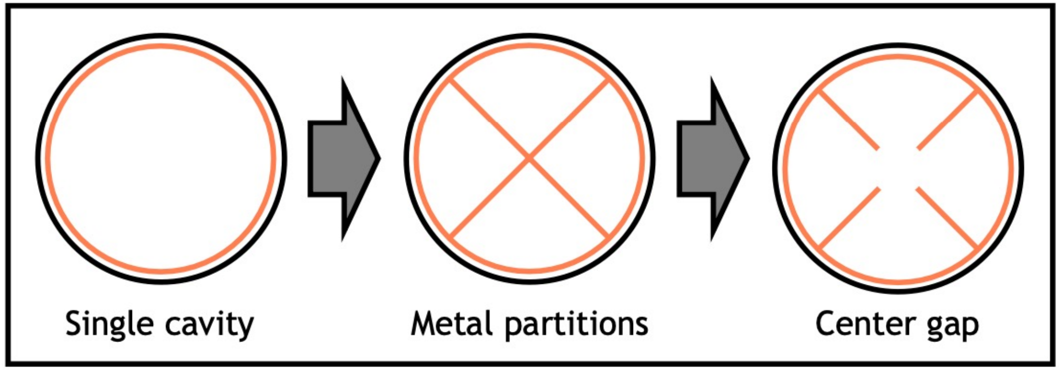
Higher frequency than the “natural” one: CAPP/DMAG and ALPHA

Doing high frequency efficiently

Multiple-cell cavity

- Multiple-cell cavity
  - New concept developed at CAPP
    1. Single cylindrical cavity fitting into the bore
    2. Split by metal partition with equidistance
    3. A narrow hole at the center

	Quad-cavity	Quad-cell	Sext-cell
Configuration			
Volume [L]	**0.62**	1.08	**1.02**
Frequency [GHz]	**7.30**	5.89	**7.60**
Q (room temp.)	19,150	19,100	16,910
Form factor	0.69	0.65	0.63
Conversion power	1.00	1.65	1.32
Scan rate	1.00	2.72	**1.98**



Multiple cavity system

- ➤ Inefficient in volume
- ➤ Multiple antennae & power combiner
- ➤ Frequency matching

Multiple-cell cavity

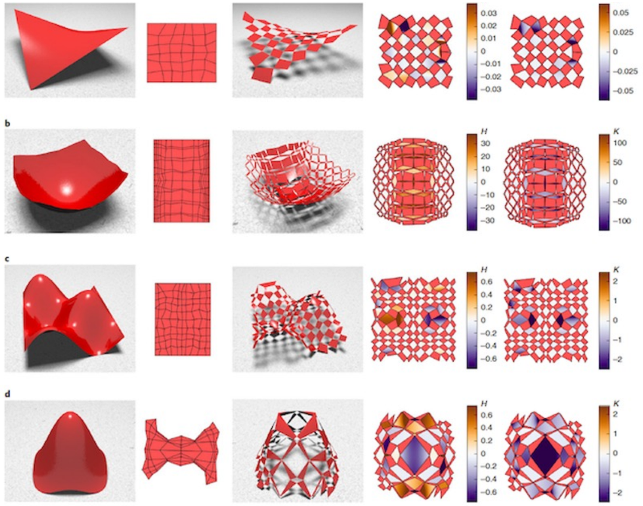
- ➤ Almost no volume loss
- ➤ Single antenna & no combiner
- ➤ Robust against tolerance

Slide by Junu Jeong, SungWoo Youn et al.

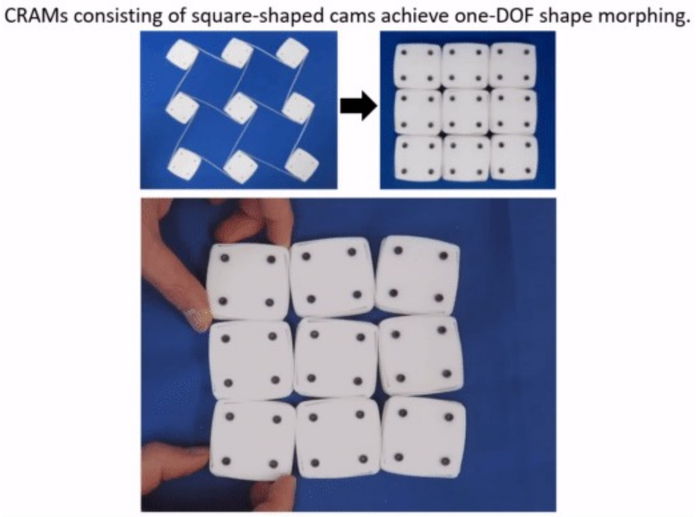
Kirigami tessellations

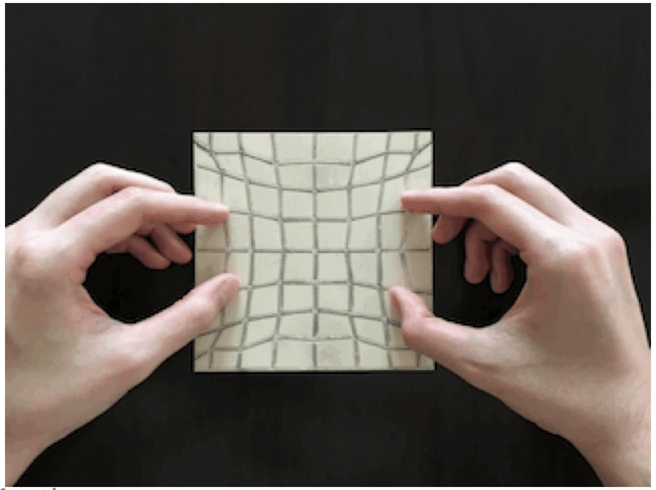
Kirigami

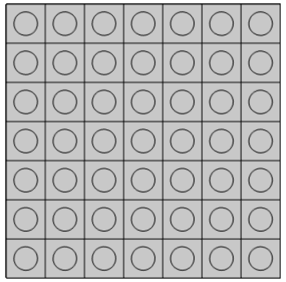
Nature material ***18****, 999*

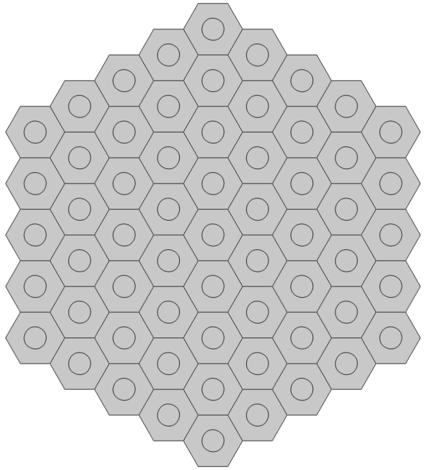


Nature communication ***9****, 4594*



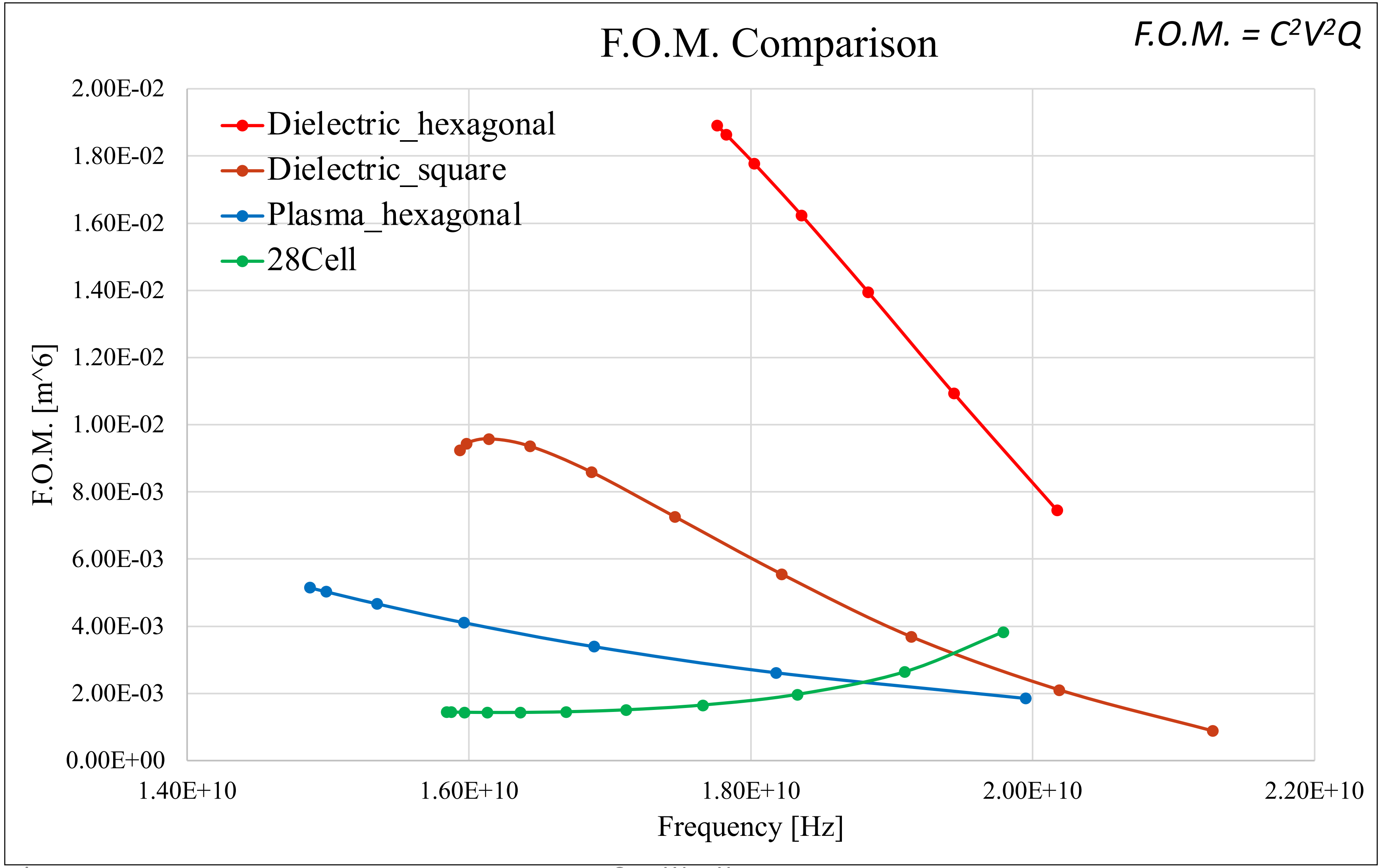






Performance comparison

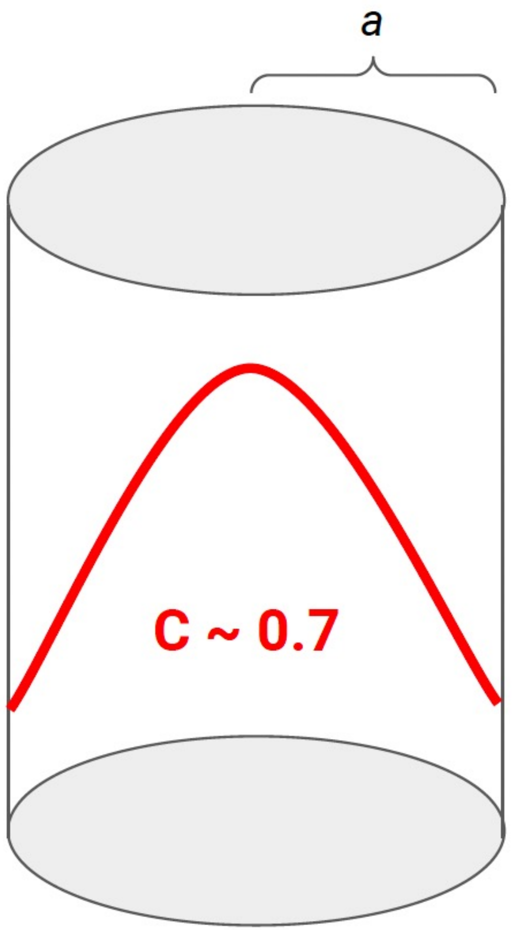
Physical Review D Vol. 107, No. 1, 015012-1-015012-8(2023)



Alpha collaboration

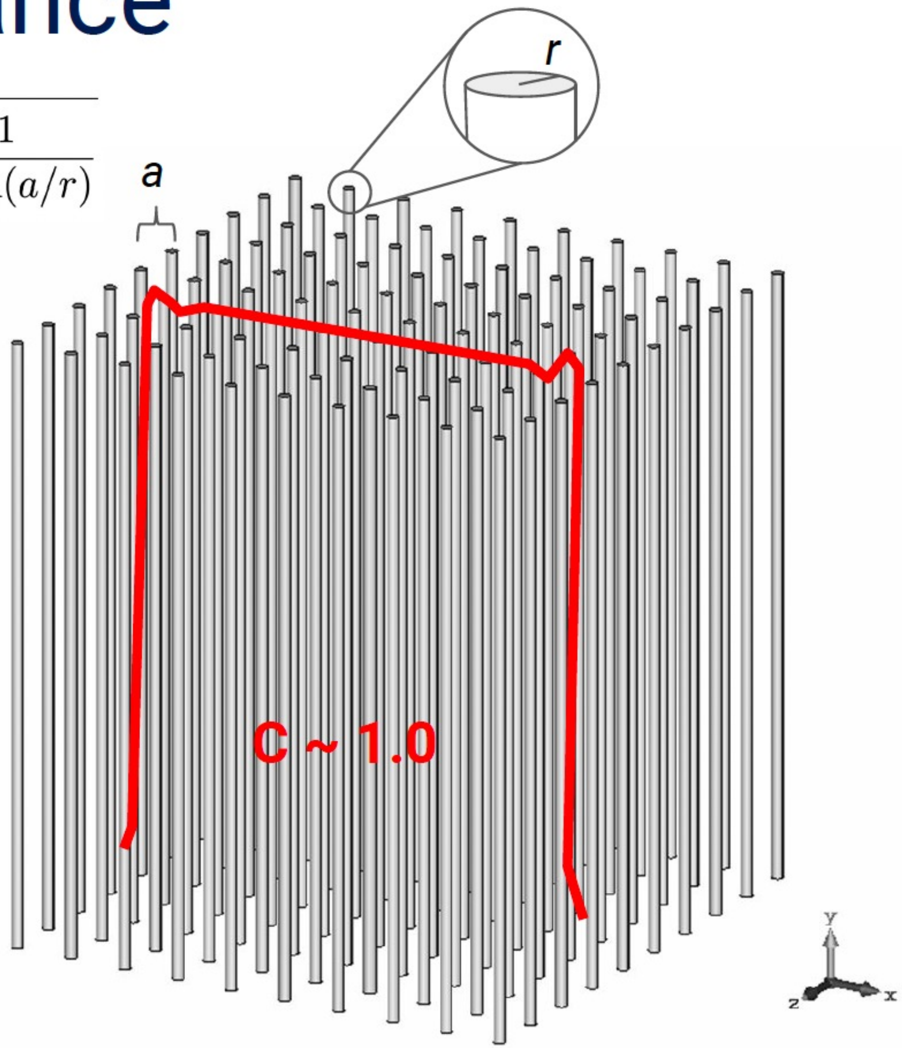
Solution: plasmonic resonance

$$f = \frac{1.202}{\pi}\frac{c}{a}$$



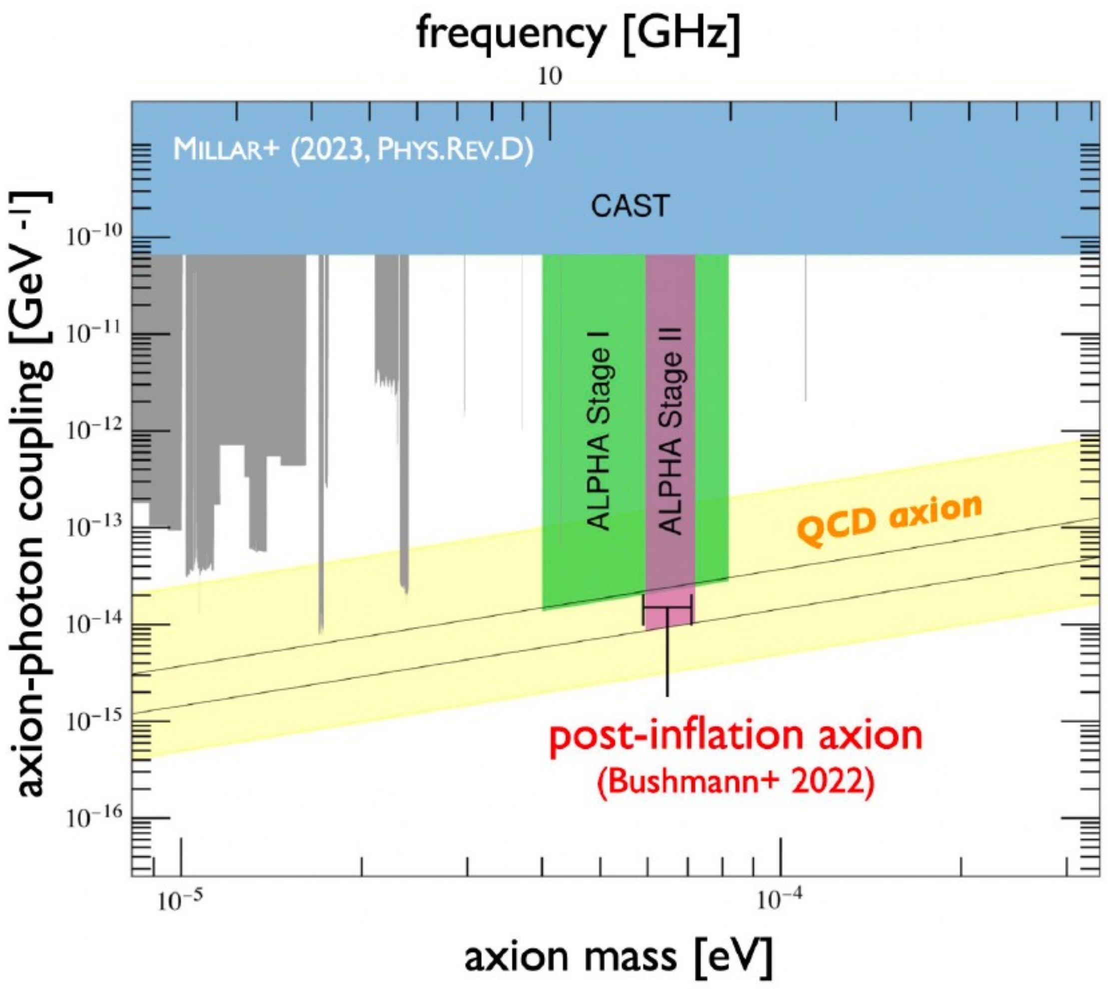
Sikivie (1983), PRL

$$f = \frac{c}{a}\sqrt{\frac{1}{2\pi\ln(a/r)}}$$



Lawson et al. (2019), PRL

Alpha collaboration



Credit: Hiranya Peiris and Alex Millar

- Post-inflation axion one of two well-motivated mass ranges
- Recent calculations: ~15 GHz, 65 μeV (Buschmann et al., 2022)
- Out of reach of conventional haloscopes, but accessible to plasma haloscopes
- ALPHA to focus initially on 40-80 μeV
- Construction of ALPHA under way, experiment hosted at Yale in high-field superconducting magnet
- Commissioning 2026-27

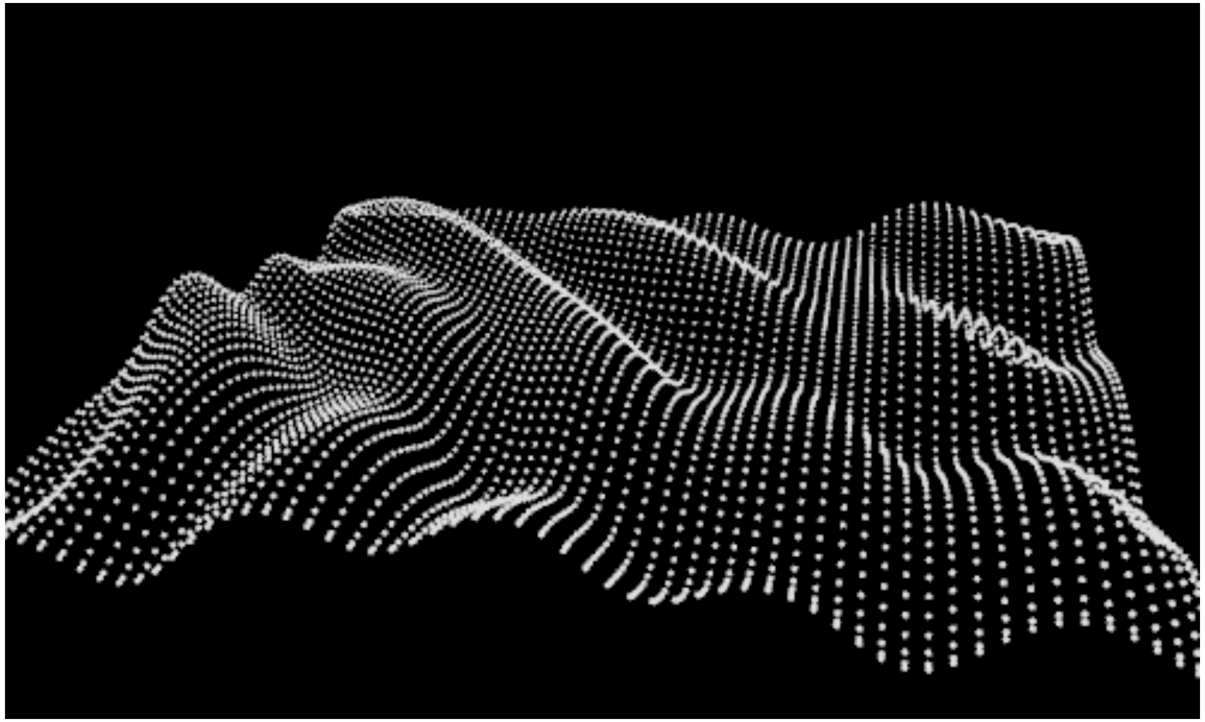
Can we do better than quantum noise?

Axion Dark Matter: a Cosmic MASER

De Broglie wavelength of axions

$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

$$\lambda \approx 300\mathrm{m} \times \left(\frac{1\mu\mathrm{eV}}{m_a}\right)$$



An immediate and practical extension of the present method would be to deploy a modest array of probing haloscopes operating in parallel. Given that vacuum fluctuations are uncorrelated between separate cavities, while the axion field remains spatially coherent over macroscopic scales, coherently combining the outputs of N detectors leads to a signal that scales as N, while the noise grows only as $\sqrt{N}$. Thus, the overall signal-to-noise ratio improves as

$$\mathrm{SNR}_{\mathrm{total}} \propto \frac{N}{\sqrt{N}} = \sqrt{N} \quad ,$$

for fixed total integration time, equivalent to a single search with a volume NV.

This strategy is justified by the fact that the axion field is expected to behave as a classical, spatially coherent oscillation over a characteristic coherence length

$$\ell_{\mathrm{coh}} \sim \frac{2\pi}{m_a v} \sim 100 \text{ m to } 1\,\mathrm{km}, \tag{30}$$

depending on the axion mass m_a (or frequency ν_a) and its virial velocity $v \sim 10^{-3}c$. For example, at $\nu_a = 1\,\mathrm{GHz}$, the coherence length is approximately 200 m, ensuring that ten or more detectors within this radius observe the same axion phase and can be summed coherently.

EO-heterodyne readout

1. Having (N) multiple cavities, located within the axion coherence length. The gain in SNR is proportional to $\sqrt{N}$, and in scanning time N.
2. The challenge: Design the experiments so that the total axion induced signal is higher than quantum noise (QN).
3. EO-heterodyning readout noise will be less than QN with 3s integration time.
4. The opportunity is indeed great. Using existing technology that can scale up easily.

Summary

- ALPHA, ADMX, CAPP→DMAG, GrAHal, HAYSTAC, QUAX,… are mature experiments, scheduled to complete the full frequency range in a few decades.
- HTS cavities can help, but the readout electronics is still the bottleneck.

- Electro-optic heterodyning (probing) readout method with Fabry-Perot resonators can enhance the scanning speed by more than an order of magnitude:
  - Great SNR, quantum noise limitations are mitigated with multiple cavities
  - Use a uniform readout system for the favorite frequency range 10 GHz $< f <$ 45 GHz.

- The new approach can be applied in the 0.5 to 50 GHz, achieving DFSZ sensitivity faster than present readouts. We can work together (in parallel) to help cover the whole range in less than 5-10 years.

Extra slides

Superconducting cavities in strong B-fields

The CAPP-MAX, our flagship experiment

based on the LTS-12T/320mm magnet

- Axion to photon conversion power at 1.15 GHz
  - KSVZ: 6.2×10^{-22} W or $\sim10^{3}$ photons/s generated
  - DFSZ: 0.9×10^{-22} W or $\sim10^{2}$ photons/s generated

- With total system noise of 300mK, $Q_0=10^5$, eff. = 0.80
  - KSVZ: 25 GHz/year
  - DFSZ: 0.5 GHz/year
- With total system noise of 200mK (250mK), $Q_0=10^5$
  - KSVZ: 50 GHz/year (35 GHz/year)
  - DFSZ: 1 GHz/year (0.64 GHz/year)
- With total system noise of 125mK, $Q_0=1\times10^6$
  - DFSZ: 1-2 GHz/year for 20% of dark matter as axions
  - DFSZ: 2-4 GHz/year, 4-8 GHz/year, 20% ADM

QUAX, INFN

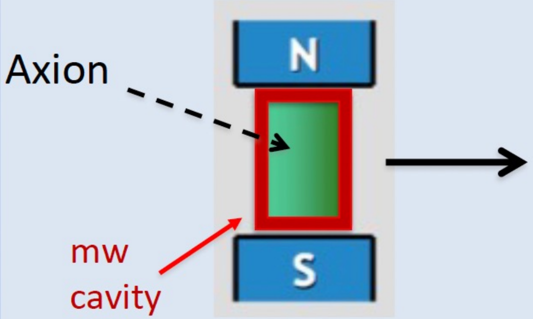
QUAX experiment in Italy

Using innovation and quantum RF-readout to make progress

QUAX – QUaerere AXion

Main Activity

- **Photon coupling: Due to the motion of the solar system in the galaxy, Dark Matter axions** are converted into **rf photons** inside a **resonant cavity** immersed in a **strong magnetic field**

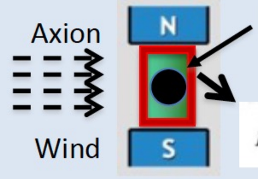


Expected rf power

$$P_a = 1.85\times10^{-25}\,\mathrm{W}\left(\frac{V}{0.0361}\right)\left(\frac{B}{2\,\mathrm{T}}\right)^2\left(\frac{g_\gamma}{-0.97}\right)^2 \times\left(\frac{C}{0.589}\right)\left(\frac{\rho_a}{0.45\,\mathrm{GeV\,cm^{-3}}}\right)\left(\frac{\nu_c}{9.067\,\mathrm{GHz}}\right)\left(\frac{Q_L}{201000}\right)$$

R&D Activity

- **Electron coupling:** the axion DM cloud acts as an **effective RF magnetic field** on electron spin exciting magnetic transitions in a magnetized sample and **producing rf photons**



Expected rf power

$$P_{\rm out} = \frac{P_{\rm in}}{2} = 8\times10^{-26}\left(\frac{m_a}{2\cdot10^{-4}\,\mathrm{eV}}\right)^3\left(\frac{V_s}{1\ \mathrm{liter}}\right)\left(\frac{n_S}{10^{28}/\mathrm{m}^3}\right)\left(\frac{\tau_{\min}}{10^{-6}\,\mathrm{s}}\right)\mathrm{W},$$

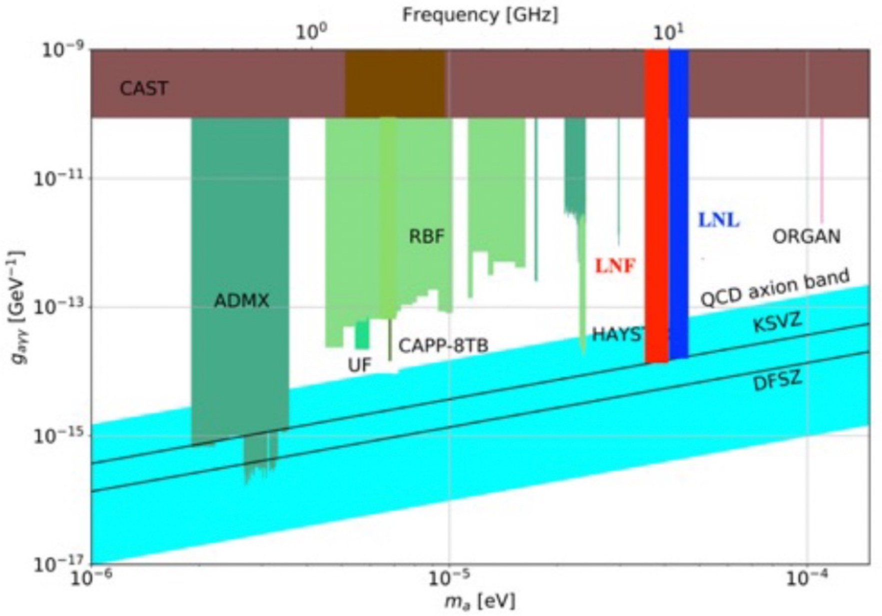
QUAX

Projection at 8.5 -11 GHz

QUAX Experiment

- The **INFN has approved the QUAX experiment** to run an observatory for searching axion via the **axion-photon coupling**
- The R&D activity on the axion – electron coupling will proceed with low priority
- **Two haloscopes** will be built: one in **Legnaro** and the other in **LNF**

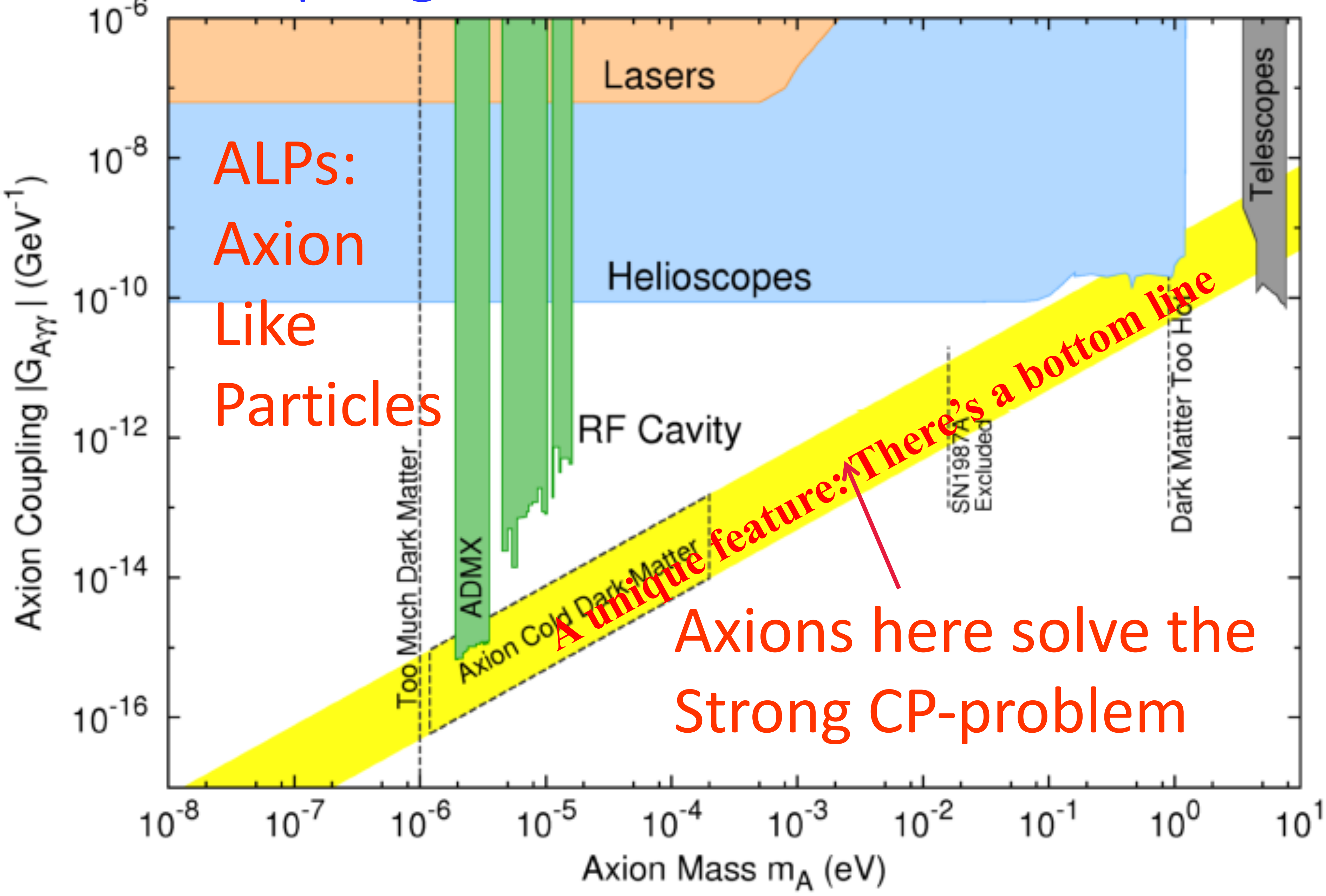
	LNF	LNL
Magnetic field	9 T	14 T
Magnet length	40 cm	50 cm
Magnet inner diameter	9 cm	12 cm
Frequency range	8.5 - 10 GHz	9.5 - 11 GHz
Cavity type	Hybrid SC	Dielectric
Scanning type	Inserted rod	Mobile cylinder
Number of cavities	7	1
Cavity length	0.3 m	0.4 m
Cavity diameter	25.5 mm	58 mm
Cavity mode	TM010	pseudoTM030
Single volume	$1.5 \cdot 10^{-4}$ m^3	$1.5 \cdot 10^{-4}$ m^3
Total volume	7⊗0.15 liters	0.15 liters
Q_0	300 000	1 000 000
Single scan bandwidth	630 kHz	30 kHz
Axion power	$7 \otimes 1.2 \cdot 10^{-23}$ W	$0.99 \cdot 10^{-22}$ W
Preamplifier	TWJPA/INRIM	DJJAA/Grenoble
Operating temperature	30 mK	30 mK



Quax 2025 projection: 2 GHz scan to the KSVZ line

- The **LNL haloscope** will be based on dielectric cavities, travelling wave parametric amplifiers and 14 T magnet
- Cryogenic system: Dilution Refrigerator to work below 60 mK

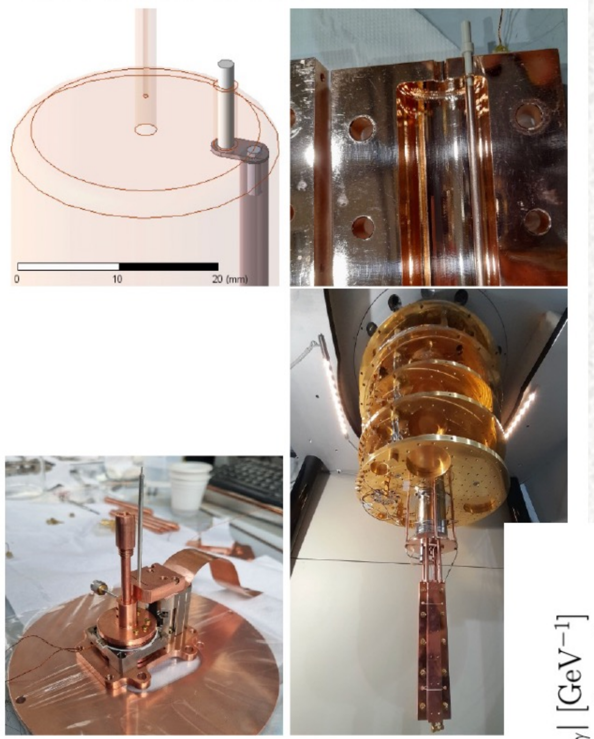
Axion coupling vs. axion mass

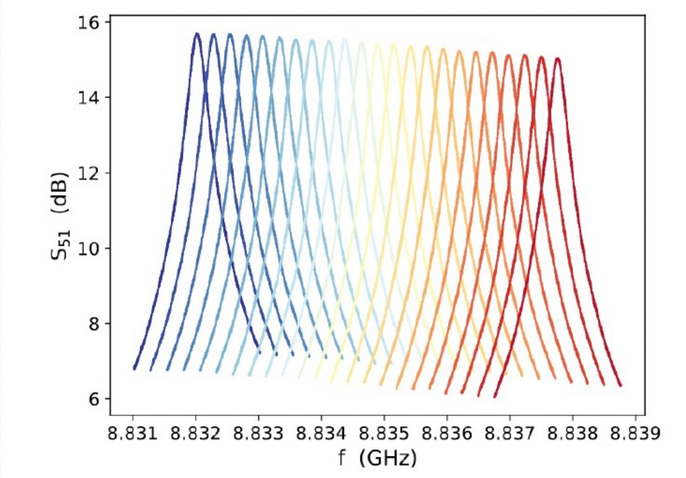


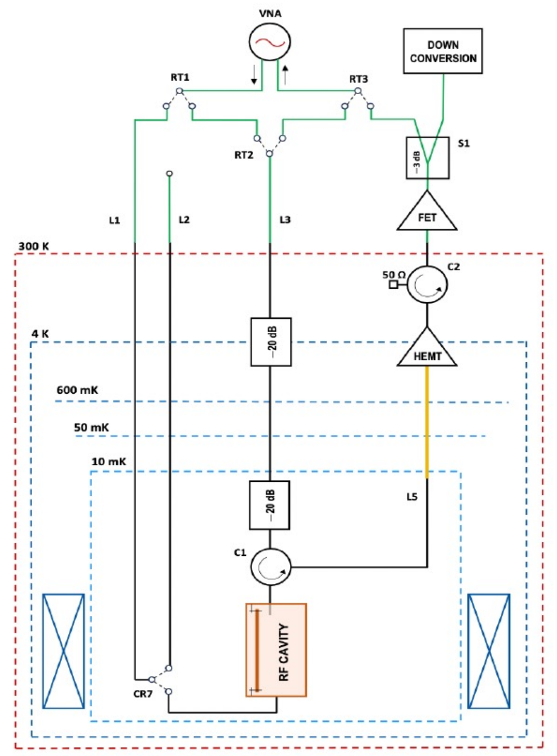
QUAX

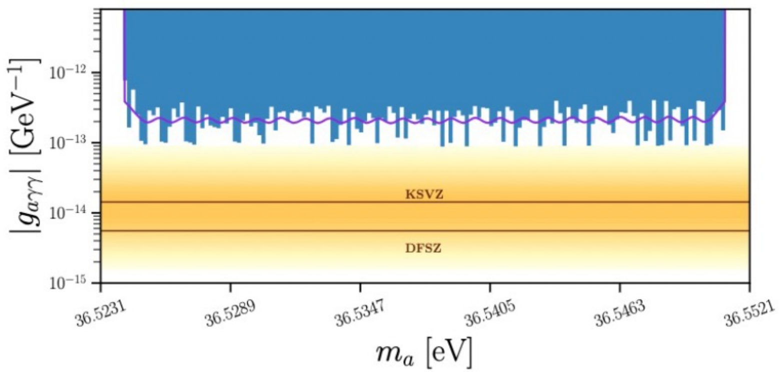
Current status
at 8.5 -11 GHz

Search for Axion dark matter with the QUAX–LNF Tunable Haloscope

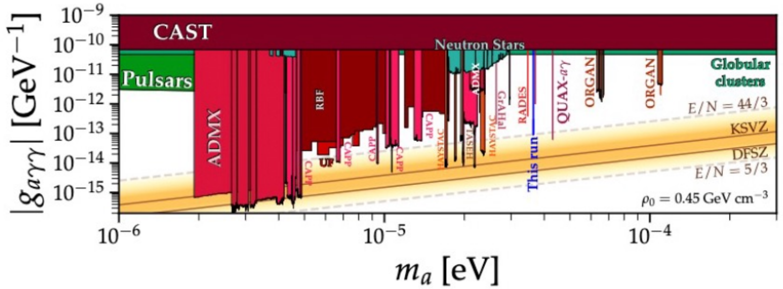








Autumn Run with JPA



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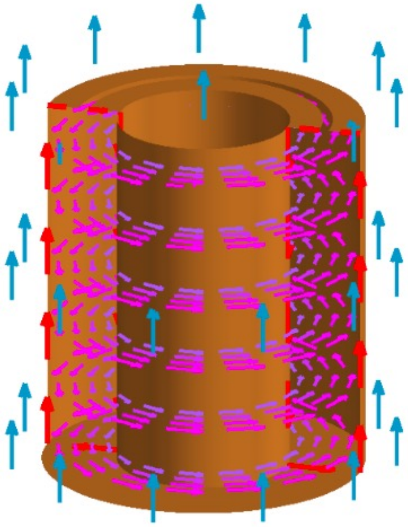
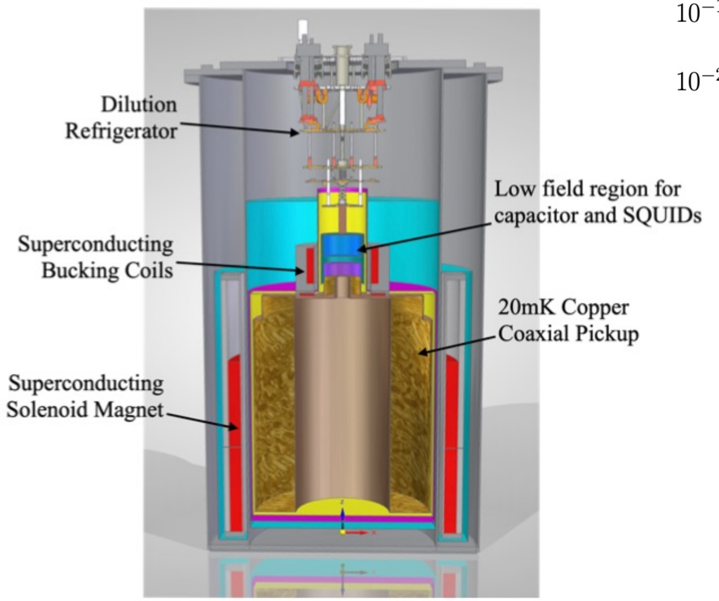
The low-frequency domain

Dark-Matter Radio, probing the low frequency axions at SLAC/USA

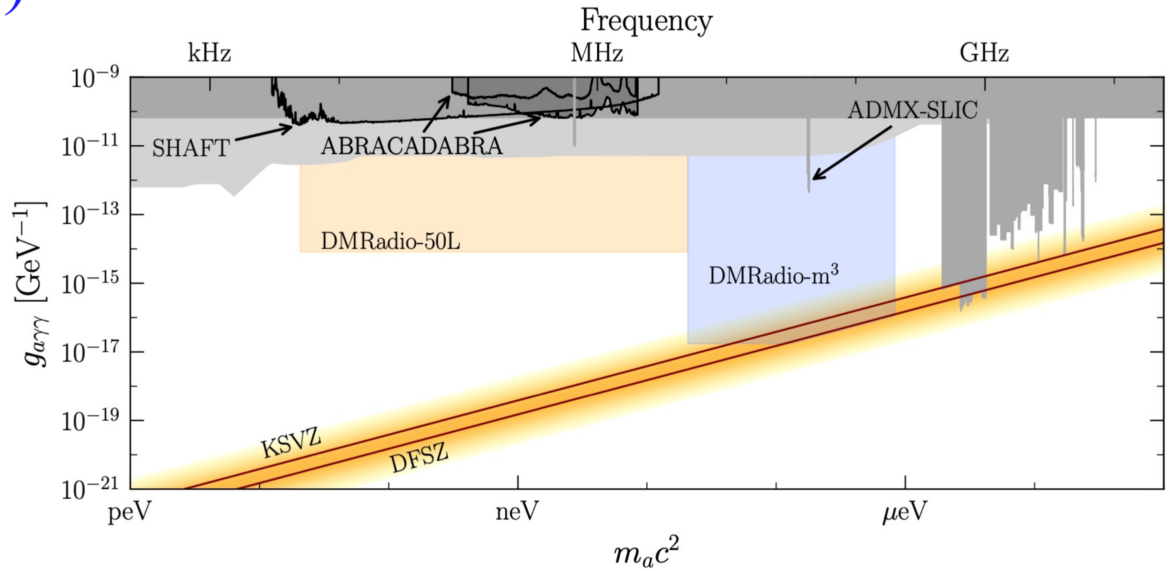
Low frequencies (long Compton wavelength) favor induction coil detection



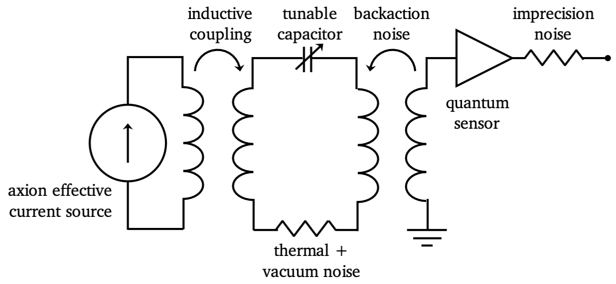
(a)



(b)



Dark Matter Radio, 2203.11246



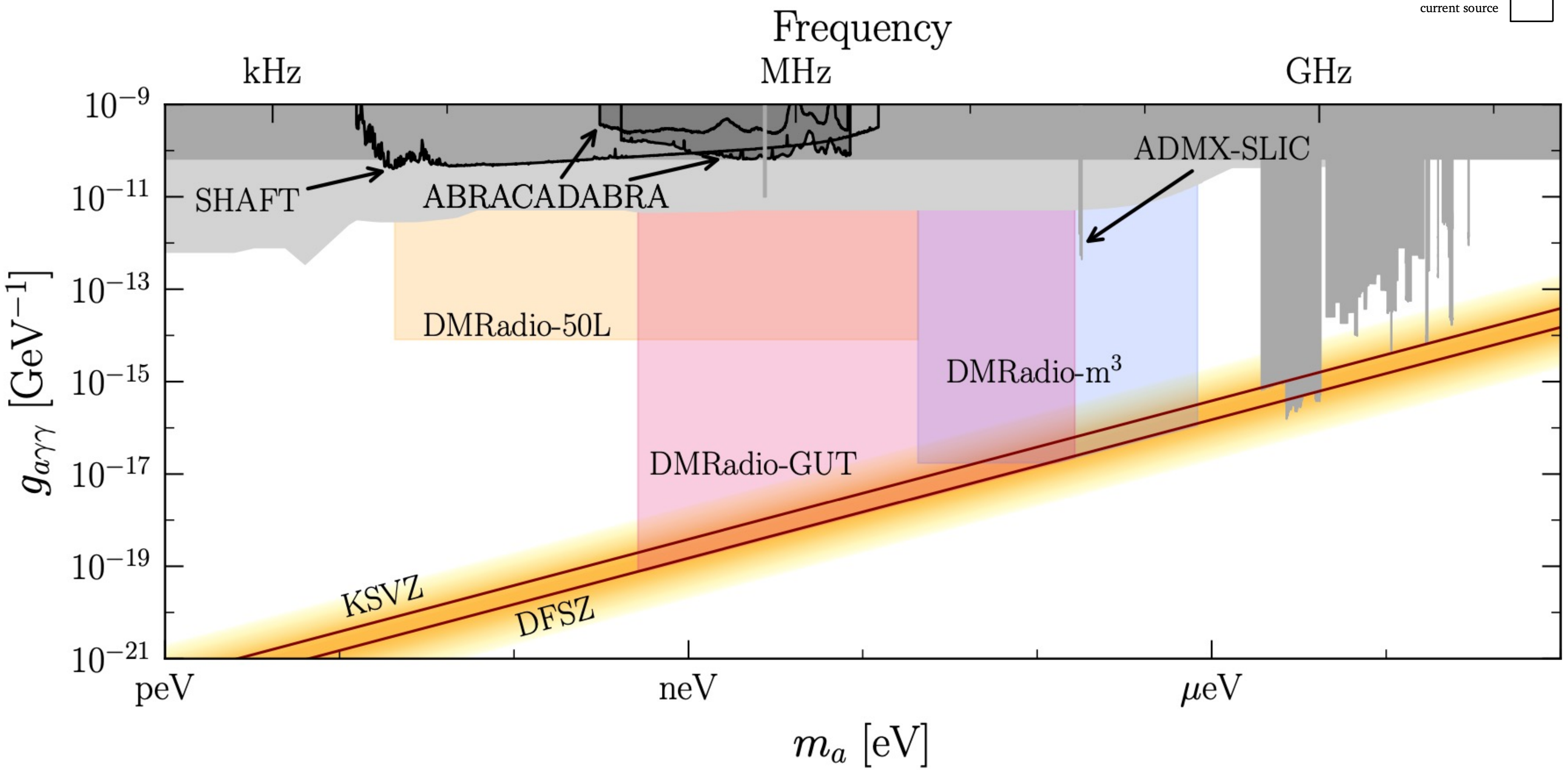


FIG. 4. Projected sensitivity for DMRadio-GUT in pink. The total scan time to cover this reach is ~ 6 years, depending on R&D outcomes. Various scenarios are outlined in Table II. Existing limits are shown in grey.

A new haloscope at Grenoble: GrAHal

New experimental effort!

B^2V wins (GrAHal-CAPP plans to scan 0.2-0.6 GHz at better than DFSZ)

9 T in 810 mm warm bore

$\langle B^2V \rangle$ at 9 T central field	Q at 4.4 K	C_{010}	Noise T	$g_{A\gamma\gamma}$
34.4 T^2m^3	1-2 10^5	0.63-0.69	1.6 K	DFSZ

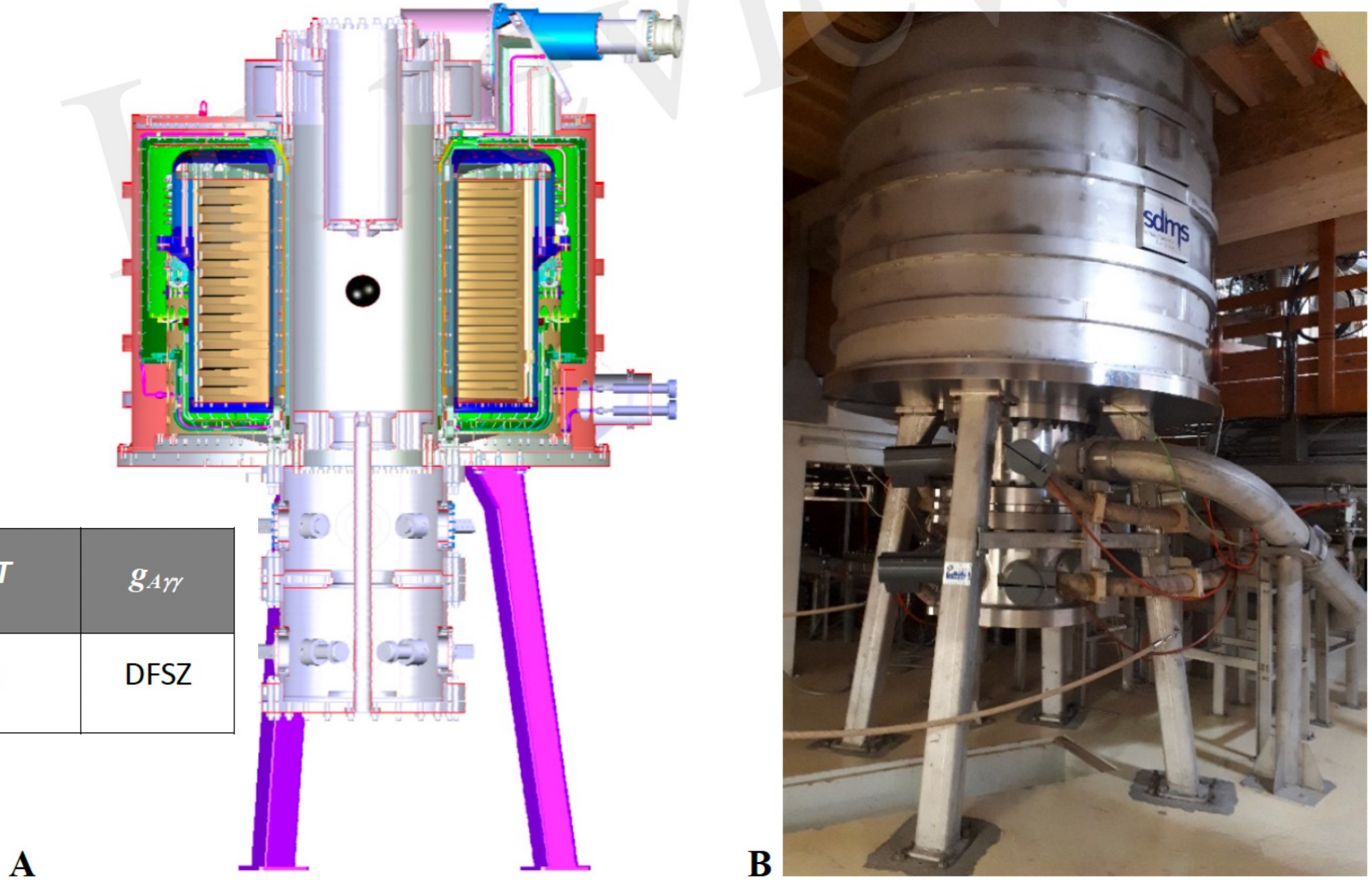


FIGURE 1
A) Cut view of the cryostat and large bore superconducting outsert of the Grenoble hybrid magnet.
B) The magnet as built in operation at LNCMI-Grenoble. The total height is about 5.4 m for a total weight of about 52 tons. Mechanical structures above and below the magnet aperture are water cooling boxes for the 24 MW resistive inserts used to reach higher magnetic fields. They will not be used for the GrAHal-CAPP haloscope described in this article.

Heterodyne-variance method, 2209.07022

Intermediate method before low-noise single photon detection

Comparisons

Junu Jeong's slide

- **SNR comparison with Single Photon Detector**

$$\mathrm{S/N}_{\sigma^2} \approx \frac{\dot N_s}{\sqrt{2f_s}}\sqrt{\Delta t} \qquad \mathrm{S/N}_{\mu} \approx \frac{\dot N_s}{\sqrt{\dot N_{\mathrm{th.}} + \dot N_D}}\sqrt{\Delta t}$$

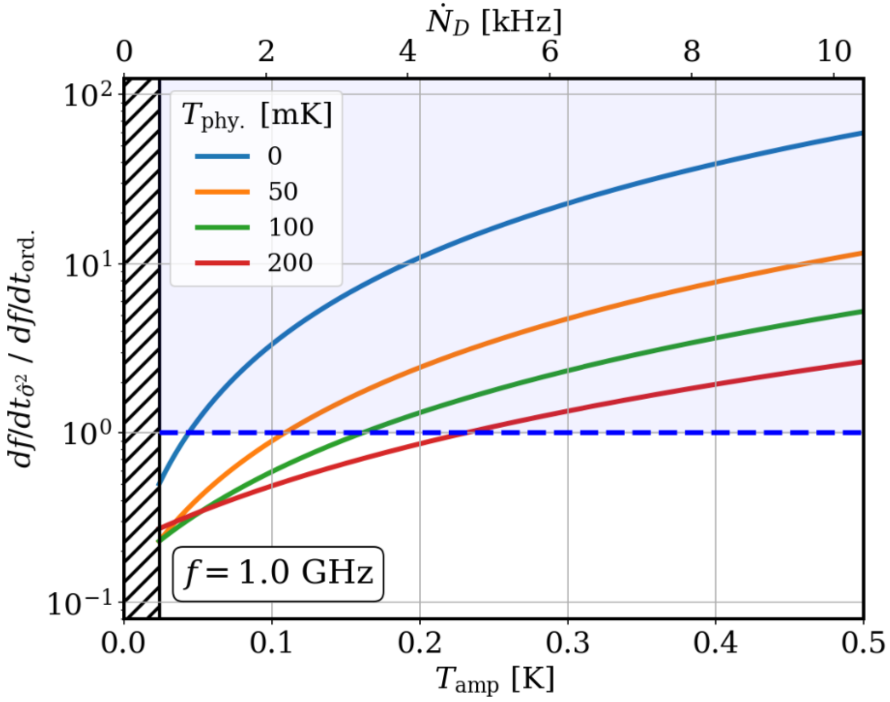
  - The denominator changes from $\sqrt{2f_s}$ to $\sqrt{\dot N_{\mathrm{th.}} + \dot N_D}$
  - In the case that $\dot N_D > 2f_s$, $\mathrm{S/N}_{\sigma^2} > \mathrm{S/N}_{\mu}$

- **Scan rate comparison with Ordinary Method**

$$\left.\frac{df}{dt}\right|_{\sigma^2} \approx \frac{\Delta f_c}{\Delta t} = \frac{\dot N_s^2}{\mathrm{S/N}_{\sigma^2}}\frac{\Delta f_c}{2\Delta f_a}$$

$$\left.\frac{df}{dt}\right|_{\mathrm{ord}} \approx \frac{\Delta f_c}{\Delta t} = \frac{1}{\mathrm{S/N}_{\mu}}\left(\frac{P_s}{k_B T}\right)^2 \frac{Q_a}{Q_l}$$

- $T_{\mathrm{amp}} \sim T_{\mathrm{QL}} = hf$: Ordinary method is fast
- $T_{\mathrm{amp}} \gtrsim 2T_{\mathrm{QL}} = 2hf$: Variance method is fast



David Tanner

Strawman: Single cavity

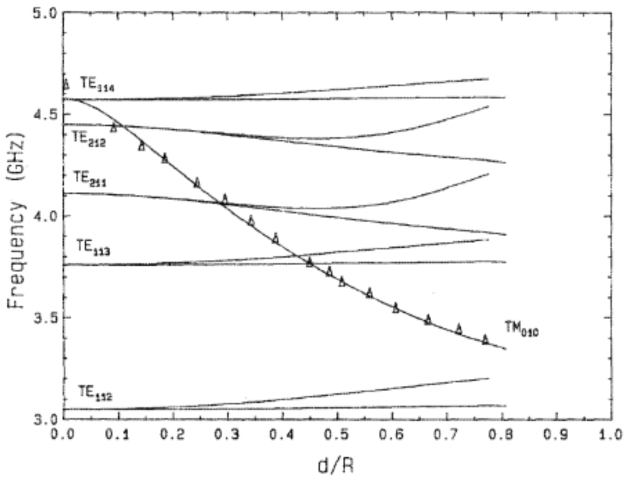
- Single cylinder, 8 T field; change size to resonate at search frequency

$$P = 130\ \mathrm{yW} \left(\frac{1\ \mathrm{GHz}}{f}\right)^{2.67}$$

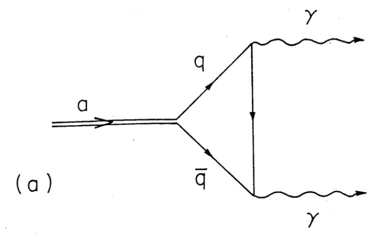
- Volume decreases as f^{-3}, the Q decreases as $f^{-2/3}$ while the mass increases as f

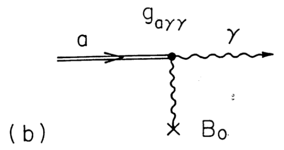
- Length as well as diameter changes because the cavity cannot get too long
  - The longer the cavity, the more TE/TEM modes there are
  - Typically:

    $L \sim 4.4r$



Axion Couplings





- Gauge fields:
  - Electromagnetic fields (microwave cavities: CAPP, ADMX,…)

$$L_{\text{int}} = -\frac{g_{a\gamma\gamma}}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu} = g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$

  -
  - Gluon Fields (Oscillating EDM: CASPEr, storage ring EDM)

$$L_{\text{int}} = \frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

- Fermions (coupling with axion field gradient, pseudomagnetic field, CASPEr-Electric, ARIADNE; GNOME)

$$L_{\text{int}} = \frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$